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Changming Qin Date

CHIRAL DIRHODIUM CATALYSTS DESIGN, SYNTHESIS AND APPLICATION IN ASYMMETRIC CARBENOID TRANSFORMATIONS AND SILVER-CATALYSIS OF VINYLOGOUS FLUORINATION

By

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Doctor of Philosophy

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M.Sc., Wenzhou University, 2008

Advisor: Huw M. L. Davies, Ph.D.

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James T. Laney School of Graduate Studies of Emory University

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Abstract

CHIRAL DIRHODIUM CATALYSTS DESIGN, SYNTHESIS AND APPLICATION IN ASYMMETRIC CARBENOID TRANSFORMATIONS AND SILVER-CATALYSIS OF VINYLOGOUS FLUORINATION

By Changming Qin

The first chapter gives an overview about carbene precursors, dirhodium catalysts and general metallocarbene transformations. Dirhodium catalysts are exceptional for transformations of diazo compounds. In contrast to acceptor only substituted metal carbenes, the rhodium-bound donor/acceptor carbenes have attenuated reactivity due to the donor group, enabling highly selective carbene reactions to be achieved. Also, the ligand around the dirhodium core can further control the reactivity and selectivity profile of carbenes.

The second chapter is devoted to exploring the D_4-symmetric dirhodium phosphonate catalysis of cyclopropanation and C–H functionalization *via* decomposition of donor/acceptor diazoacetates. The combination of 3,4-dimethoxyphenyldiazoacetate with enantiomerically pure Rh_2(*R*-BNP)$_4$ in the presence of styrene affords a cyclopropane moiety in highly diastereo- and enantioselective fashion. The newly designed dirhodium phosphonate Rh_2(*S*-CBNP)$_4$ proves to catalyze highly selective C–H functionalization of 1,4-cyclohexadiene with 3,4-dimethoxyphenyldiazoacetate.

The third chapter describes the development of dirhodium tetrakis-(*R*)-(1-(4-bromophenyl)-2,2-diphenylcyclopropane carboxylate) [Rh_2(*R*-BTPCP)$_4$], which was found to be an effective chiral catalyst for enantioselective reactions of aryl- and styryldiazoacetates. Cyclopropanations, tandem cyclopropanation/Cope rearrangements and a combined C–H functionalization/Cope rearrangement were also achieved using Rh_2(*R*-BTPCP)$_4$ as catalyst in highly enantioselective manner. The advantages of Rh_2(*R*-BTPCP)$_4$ include its ease of synthesis and its tolerance to the size of the ester group in the styryldiazoacetates and the use of dichloromethane as solvent. Computational studies suggest that the catalyst adopts a D_2-symmetric arrangement, but when the carbene binds to the catalyst, two of the ligands rotate outwards to make room for the carbenoid and the approach of the substrate to the carbenoid.

The fourth chapter focuses on enantioselective synthesis of 2-arylbicyclo[1.1.0]butane-carboxylates. The dirhodium-catalyzed reaction of 2-diazo-5-arylpent-4-enoates can be controlled by appropriate choice of catalyst and catalyst loading to form either 2-arylbicyclo[1.1.0]butane carboxylates or cyclohexene derivatives. Both products are produced in a highly diastereoselective manner, with 2-arylbicyclo[1.1.0]butane carboxylates preferentially formed under low catalyst loadings. When the reaction is catalyzed by Rh_2(*R*-BTPCP)$_4$, the 2-arylbicyclo[1.1.0]butane carboxylates are generated with high levels of asymmetric induction.

The fifth chapter concentrates on vinylogous transformations of metallovinylcarbenes. An enantioselective formal [3+2]-cycloaddition between nitrones and vinyldiazoacetates was first described. Rhodium-catalyzed reaction of vinyldiazoacetates with nitrones results in a formal [3+2]-annulation to generate 2,5-dihydroisoxazoles with high levels of asymmetric induction. The cascade reaction begins with a vinylogous addition event, followed by a Mannich-type ring-closure/hydride migration/alkene isomerization cascade. Dirhodium tetrakis(triarylcyclopropane carboxylates) are the optimum catalysts for this process.

The sixth chapter describes a silver-catalyzed vinylogous fluorination of vinyldiazoacetates in the presence of triethyl amine-hydrofluoride, generating important γ-fluoro-α,β-unsaturated carbonyl building blocks. Application of this method to the fluorination of farnesol and steroid derivatives was achieved.

The seventh chapter further emphasizes the importance of sterically demanding dirhodium tetrakis(triarylcyclopropane carboxylates) in site selective C–H functionalization. The established dirhodium tetraprolinate-catalyzed reactions of aryldiazoacetates cause preferential C–H functionalization of secondary C–H bonds due to competing steric and electronic effects. The more sterically demanding dirhodium tetrakis(triarylcyclopropane-carboxylate) catalysts, exemplified by dirhodium tetrakis-[(*R*)-(1-(biphenyl)-2,2 diphenylcyclopropane carboxylate)] (Rh_2(*R*-BPCP)$_4$), favor C–H functionalization of primary C–H bonds. Highly site selective and enantioselective C–H functionalization of a variety of simple substrates containing primary benzylic, allylic and methoxy C–H bonds was achieved with this catalyst. The utility of this approach has been demonstrated in the late-stage primary C–H functionalization of (-)-α-cedrene and a steroid.

CHIRAL DIRHODIUM CATALYSTS DESIGN, SYNTHESIS AND APPLICATION IN ASYMMETRIC CARBENOID TRANSFORMATIONS AND SILVER-CATALYSIS OF VINYLOGOUS FLUORINATION

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For my parents

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Chapter I
Introduction to Rhodium Carbene Chemistry

1.1 Rhodium carbenes

The chemistry of rhodium carbene intermediates has broad application in organic synthesis.[1] A pivotal element associated with this chemistry is the design and development of novel chiral dirhodium catalysts with unique properties.[2] The central theme in this thesis is to design and develop highly symmetric and sterically demanding chiral dirhodium catalysts and advance the art of asymmetric carbene transformations by applying them to previously unknown or poorly developed reactions. This chapter will discuss the fundamental aspects of rhodium carbenes, with a particular emphasis on how they relate to the theme of this thesis.

Free carbenes are highly reactive species that usually undergo non-selective organic transformations; however, through tuning the substituents and even the metals bound to carbenes, the reactivity and selectivity of carbenes can be modulated.[3] In recent years, the rhodium-stabilized carbenes generated upon decomposition of diazo compounds have emerged as attractive intermediates in organic synthesis.[4] Among the type of rhodium carbenes studied (Figure 1.1), the donor/acceptor rhodium carbenes enjoy great priority in organic synthesis, especially in asymmetric intermolecular carbene transformations.

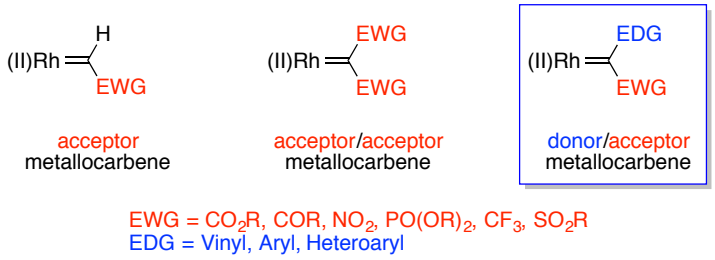
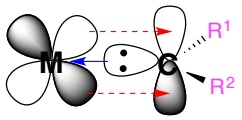


Figure 1.1 Three types of metallocarbene

The reason why donor/acceptor rhodium carbenes have great advantages to participate in more selective carbene transformations than those of conventional acceptor-only and acceptor/acceptor rhodium carbenes is that these intermediates are much more stabilized due to the donor substituents, as can be seen from the resonance structure of these intermediates.[4] Also, the stabilization stems from π-back bonding to the carbene with the d-orbital of rhodium (Figure 1.2).[4] In the Davies group, the study of donor/acceptor rhodium carbenes has been the major focus and the aim of this thesis was to advance the art of donor/acceptor rhodium carbene transformations by design of new sterically bulky chiral dirhodium catalysts.



lone pair on carbon to metal: stong-C-M α–bond

d electrons to p orbital on carbon
; weak-moderate π–bond, stabilize carbene slightly but still maintain its enough electrophilicity

desired metal: binds to the carbene through strong α–acceptor interaction and weak back donation

when R^1 or R^2 is electron-donating group, it further stabilizes the carbene

Figure 1.2 Factors that stabilize the metallocarbenes

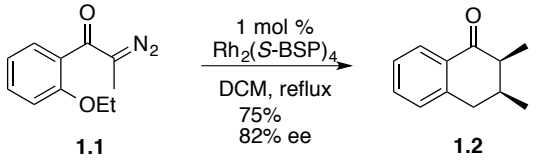
1.2 Dirhodium catalysts

Dirhodium catalysts play major roles and have advanced many possibilities in current metallocarbene chemisty.[2] The reactivity and selectivity of the resulting rhodium carbene intermediates are not only controlled by the substituents on carbenes, but they are controlled by the nature of dirhodium catalysts. The property of dirhodium catalysts can be finely tuned by choosing the appropriate ligands. In general, rhodium complexes containing electron-deficient and sterically less demanding ligands would result in much more reactive rhodium carbenes upon decomposition of diazo compounds, undergoing less selective carbene transformations. On the other hand, rhodium complexes bearing electron-rich and sterically congested ligands would lead to less reactive rhodium carbenes, participating in more selective carbene transformations. The purpose of this thesis was to design a family of electron-rich and sterically bulky ligands to access a novel class of dirhodium catalysts, which would be expected to participate in more selective carbene transformations.

The development of effective chiral dirhodium catalysts has been the key to the success of asymmetric carbene chemistry. Unlike the design of other metal catalysts such as copper and ruthenium in carbene chemistry, which needs ligands with C_2, D_2 and even D_4-symmetry,[2] the highly symmetric dirhodium acetate core provides a great platform for design of high symmetry dirhodium complexes with low symmetric ligands. A concise summary of the key dirhodium catalyst previously studied is listed below, with a particular focus on how they relate to the theme of this thesis.

1.2.1 Dirhodium carboxylates

The chiral dirhodium carboxylate catalysts were originally synthesized by Brunner and co-workers in 1989, but the initial evaluation of these type of catalysts in cyclopropanation of styrene upon decomposition of ethyl diazoacetate resulted in less than 12% ee.[5] The consideration of the long distance between the chiral center in chiral carboxylate and the axial active site of dirhodium led to a preliminary assumption that chiral dirhodium carboxylate complexes would not be effective in asymmetric carbene transformations.[6] McKervey and co-workers, however, discovered that dirhodium prolinate complex,[7] Rh_2(*S*-BSP)$_4$ can selectively catalyze the intramolecular C–H insertion upon decomposition of diazoketone compound (**1.1**), affording the product (**1.2**) in 82% ee (Scheme 1.1).



Scheme 1.1 Rh_2(*S*-BSP)$_4$-catalyzed intramolecular C–H insertion reaction

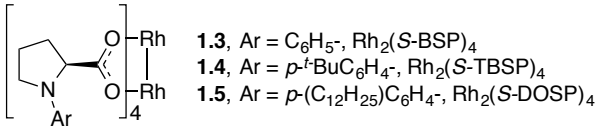
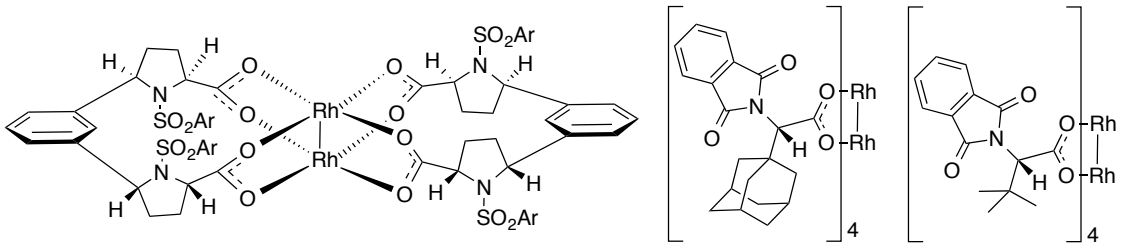


Figure 1.3 Dirhodium prolinate catalysts

This discovery quickly led to the synthesis of Rh_2(*S*-TBSP)$_4$ (**1.3**) by the Davies group. It was found that the nature of the solvent has a dramatic effect on the asymmetric induction in the chiral dirhodium carboxylate-catalyzed carbene reactions.[8] Hydrocarbon solvents such as hexane gave much better enantioselectivity than polar solvents like dichloromethane in the cyclopropanation reactions. To increase the solubility of

dirhodium catalysts in hydrocarbon solvents, the Davies group developed Rh_2(*S*-DOSP)$_4$ (**1.5**) containing a dodecyl chain in the ligand, which is very soluble in hydrocarbon solvents, even at -78 °C. This early study was very important, as the combination of Rh_2(*S*-DOSP)$_4$ and donor/acceptor diazoacetates in hydrocarbon solvents has advanced many possibilities in carbene chemistry, especially in the intermolecular asymmetric carbene transformations.



1.6, Rh_2(*S*-biTISP)$_2$, Ar = 2,4,6-*tri*-*i*PrC$_6$H$_2$ **1.7**, Rh_2(*S*-PTAD)$_4$ **1.8**, Rh_2(*S*-PTTL)$_4$

Figure 1.4 Structures of Rh_2(*S*-biTISP)$_4$, Rh_2(*S*-PTAD)$_4$ and Rh_2(*S*-PTTL)$_4$

The use of hydrocarbon solvents, however, is not a very good choice in organic synthesis, especially in the industrial production since not all the organic molecules are soluble in these solvents. Although the use of large amounts of hydrocarbon solvents could help solve the solubility issues, this approach is not cost-effective because a solvent like 2,2-dimethylbutane is extremely expensive. To address this issue, the Davies group then designed the second generation dirhodium catalysts by simply bridging the *N*-arylsulfonyl proline ligand together, providing the conformational limited Rh_2(*S*-biTISP)$_2$ (**1.6**) because the conformational mobility of Rh_2(*S*-DOSP)$_4$ was thought to be the reason for hydrocarbon solvent-dependent enantioselectivity. As expected, the Rh_2(*S*-biTISP)$_2$-catalyzed carbene transformations did not show dramatic solvent effects in certain asymmetric carbene transformations,[9] but the tedious synthesis of this catalyst eroded the appeal. One aim of this thesis was to design a new type of chiral dirhodium catalysts with

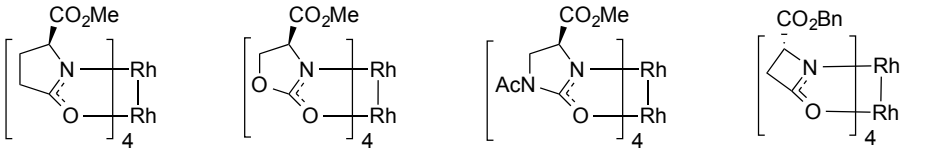
limited conformational change that would be synthesized concisely and would result in high asymmetric induction in a diverse range of solvents.

The other important type of chiral dirhodium carboxylate catalysts, initially developed by the Hashimoto group, is the phthalimido catalysts such as Rh_2(*S*-PTTL)$_4$ (**1.8**),[10] which has been utilized in a variety of asymmetric carbene transformations. An analog of Rh_2(*S*-PTTL)$_4$ developed in the Davies group is Rh_2(*S*-PTAD)$_4$ (**1.7**). It became the third generation of chiral dirhodium catalysts in the Davies group to catalyze a diverse range of carbene transformations that Rh_2(*S*-DOSP)$_4$ failed to give high asymmetric induction, including a range of different acceptor group on the donor/acceptor carbenoids.[11-14] The initial synthesis of Rh_2(*S*-PTAD)$_4$ employed a Rh_2(*S*-DOSP)$_4$-catalyzed enantioselective C-H functionalization of adamantane as the key step.[15] One purpose of this thesis was to see whether asymmetric cyclopropanation transformations developed in the Davies group would help the design of new scaffolds for chiral dirhodium catalysts.

The symmetry of the catalyst has been considered to be an important factor for the high asymmetric induction exhibited by certain chiral dirhodium catalysts.[2] Rh_2(*S*-DOSP)$_4$, has been proposed to adopt a D_2 symmetrical arrangement especially in non-polar hydrocarbon solvents to reduce the overall dipole of the complex.[8b] The proposed D_2-symmetric model of this catalyst illustrates the observed solvent effects and stereoselectivity, including the prediction of the observed absolute stereochemical outcome in certain transformations.[16] The bridged dirhodium catalyst Rh_2(*S*-biTISP)$_4$, is considered to be in a locked D_2-symmetric arrangement, and consequently, shows better solvent tolerance for inducing high asymmetric induction.[2]

1.2.2 Dirhodium carboxamidates

A family of chiral dirhodium carboxamidates originally developed by the Doyle group was derived from enantiomerically pure 2-oxopyrrolidine, 2-oxazolidinone, *N*-acylimidazolidin-2-one and 2-azetidinone ligand (Figure 1.5).[1a]



1.9, Rh_2(5*S*-MEPY)$_4$ **1.10**, Rh_2(4*S*-MEOX)$_4$ **1.11**, Rh_2(4*S*-MACIM)$_4$ **1.12**, Rh_2(4*S*-BNAZ)$_4$

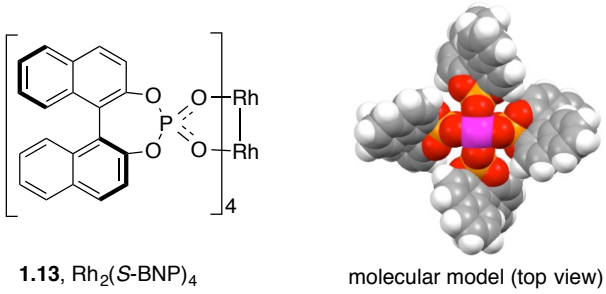
Figure 1.5 Structure of standard dirhodium carboxamidates

Dirhodium carboxamidates are more electron-rich catalysts because of the relatively high basicity of carboxamide ligands than those of carboxylate ligands, which make them less reactive than dirhodium carboxylates. These catalysts have shown to be very effective in catalysis of decomposition of diazoacetates and diazoacetamide derivatives; a variety of carbene transformations have been achieved in highly stereoselective fashion such as intramolecular cyclopropanation,[17] intramolecular C–H insertion reactions,[18] and hetero-Diels-Alder reactions.[19]

1.2.3 Dirhodium phosphonates

The Pirrung group originally developed a family of dirhodium phosphonate catalysts in 1992. They were derived from C_2-symmetric binaphthylphosphonate ligand.[20] They are very electron-deficient because of the lower basicity of phosphonate ligands and thus would be more reactive than those of dirhodium carboxylate catalysts. Due to the C_2-symmetric binaphthylphosphonate ligand, the overall dirhodium complex would have a D_4-symmetry as illustrated by Rh_2(*S*-BNP)$_4$ (Figure 1.6). The higher symmetry dirhodium catalysts would decrease the possible orientations for the bound carbene, and this could conceivably lead to higher asymmetric induction in the carbene reactions.

However, the utilization of the binaphthylphosphonate catalysts has met with limited success[21] One theme of this thesis is to discuss the previous major success and limitations with this family of catalyst in carbene transformations and compare with our recent results when donor/acceptor diazoacetates were used.



1.13, Rh_2(*S*-BNP)$_4$ molecular model (top view)

Figure 1.6 Structure of Rh_2(*S*-BNP)$_4$ and its molecular model

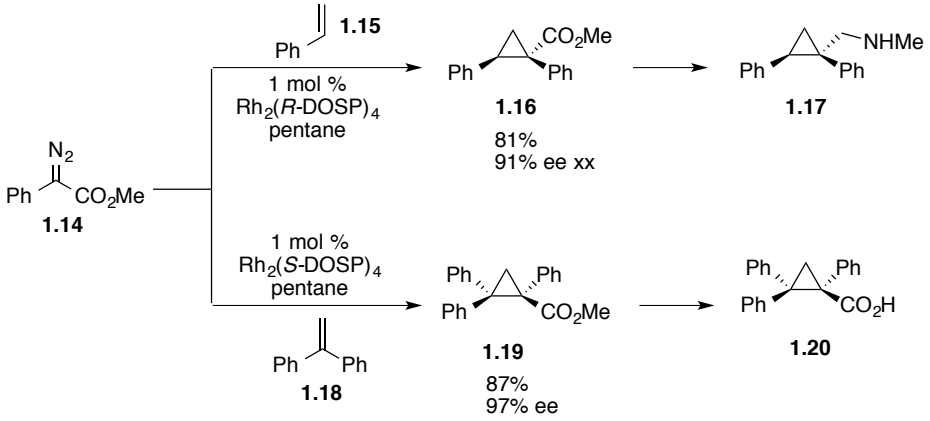
1.3 Rhodium carbene transformations

The standard cyclopropanation, C-H functionalization and vinylogous transformations of rhodium carbenes will be concisely discussed in this part, with particular discussions on how these transformations relate to the theme of this thesis and the mechanistic studies in these transformations.

1.3.1 Cyclopropanation

The metal-catalyzed decomposition of diazo compounds in the presence of alkenes is a general method for the stereoselective synthesis of cyclopropanes.[4] In the Davies group, the Rh_2(DOSP)$_4$-catalyzed cyclopropanation reaction between methyl aryldiazoacetates and olefins provided highly enantioenriched cyclopropanes.[22] For example, the cyclopropanation of styrene (**1.15**) and 1,1-diphenylethylene (**1.18**) upon decomposition of phenyldiazoacetate (**1.14**) afforded the cyclopropane product in high yield and enantioselectivity (Scheme 1.2). These enantioenriched cyclopropanes were utilized in a

medicinal chemistry program in the Davies group by simple conversion the esters into amines; the examination of cyclopropane amines (**1.17**) as active pharmaceutical reagents for central nervous system disease is an active project in the Davies group. One theme of this thesis was to discuss some other utilities of the enantioenriched cyclopropane carboxylic acid such as (**1.20**) as chiral ligand for dirhodium catalyst design.[23]



Scheme 1.2 The utility of enantiopure cyclopropane ester

The scope of highly asymmetric cyclopropanation by use of Rh_2(*S*-DOSP)$_4$ was limited to the use of methyl ester as acceptor group. The use of Rh_2(*S*-PTAD)$_4$ as catalyst expanded the scope of acceptor group while keeping high asymmetric induction in cyclopropanation reactions. The successful acceptor groups included phosphonates,[11] trifluoromethyl,[12] keto[13] and cyano[14] groups (Figure 1.7). One topic of this thesis is to discuss the issues of the size of ester in Rh_2(*R*-DOSP)$_4$-catalyzed cyclopropanation reactions and how to address these issues through bulky catalyst design and the advantages of using a bulky ester in carbene chemistry.

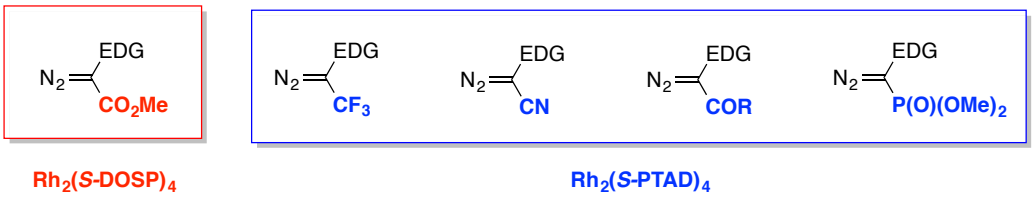
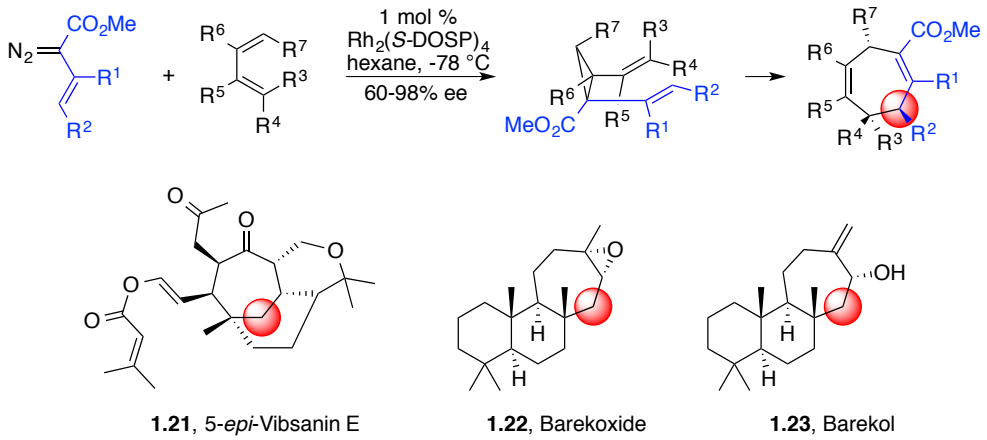


Figure 1.7 Dirhodium catalysts and their favored diazo compounds

An extension of the cyclopropanation chemistry is the combination with a Cope rearrangement when vinyldiazoacetates and dienes are used in the reaction.[24] The rhodium-catalyzed tandem cyclopropanation/Cope rearrangement results in a direct and highly enantioselective synthesis of a variety of cycloheptadienes containing multiple stereogenic centers. The utility of this methodology has been demonstrated as a key step in a number of natural product total syntheses[25] (Scheme 1.3). Particularly, it was required to use hexane as solvent to achieve high asymmetric induction, but this thesis will discuss the use of dichloromethane in highly asymmetric cyclopropanation/Cope rearrangement reactions by use of new chiral dirhodium catalysts.



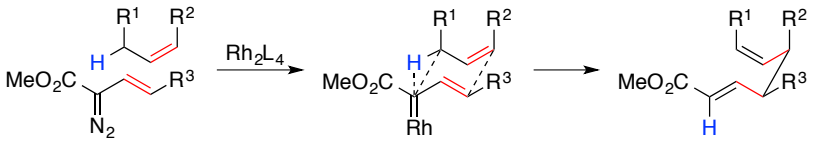
Scheme 1.3 Cyclopropanation/Cope rearrangement and its synthetic application

As for the mechanistic insights on rhodium-catalyzed cyclopropanation, a predictive "end-on" model for intermolecular cyclopropanation reactions was initially developed in 2003.[26] In this recent computational study, the substrate approaches the rhodium center

with an "end-on" manner; the dihedral angle of the carbon-carbon double bond in styrene and the carbon-rhodium double bond in the metallocarbene is about 15°. In this transition state, the calculated bond length of C1-C2 was 2.278Å, whereas the bond length of C1-C3 was calculated as 2.844Å. These data supported the cyclopropanation proceeded through a concerted but highly asynchronous mechanism.[26]

1.3.2 C–H functionalization

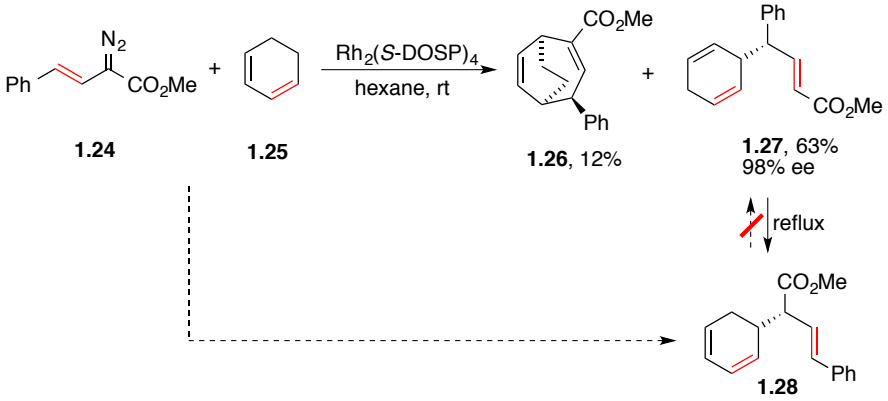
Donor-acceptor rhodium carbenes have proven to be attractive intermediates for selective intermolecular C–H functionalization.[2] In contrast to the traditional rhodium carbenes, which required a large excess of trapping reagents to minimize carbene dimerization, the donor/acceptor rhodium carbenes can be conducted with only a slight excess of trapping agents. This thesis will further emphasize this advantage in selective intermolecular C–H functionalization. Also, previous studies with Rh_2(*S*-DOSP)$_4$ as catalyst in intermolecular C–H functionalization favored the activated secondary C–H bonds due to a balance of steric and electronic effects.[2] One major theme of this thesis is to discuss how to advance the concept of selective intermolecular C–H functionalization through the use of bulky chiral dirhodium catalyst design.



Scheme 1.4 The combined C–H functionalization/Cope rearrangement

An extension of C–H functionalization chemistry is the combined C–H functionalization/Cope rearrangement reaction between compounds with allylic C-H bonds and vinylcarbenoids[27] (CHCR, Scheme 1.4). The discovery of this unusual transformation came form the initial study on cyclopropanation/Cope rearrangement in

the reaction of vinyldiazoacetate (**1.24**) and 1,3-cyclohexadiene (**1.25**) (Scheme 1.5). The 1,4-cyclohexadiene (**1.27**) was generated as the major product in 63% yield with 98% ee with the expected cyclopropanation/Cope rearrangement product (**1.26**) as a minor product (Scheme 1.13).[29] It was assumed that the product (**1.27**) was generated by means of a Cope rearrangement of the direct C–H insertion product (**1.28**), but this is not the case because compound (**1.27**) is the kinetic product and slowly rearranged into product (**1.28**) in refluxing hexane. Accordingly, it was proposed that the 1,4-cyclohexadiene (**1.27**) is a kinetically favored product generated *via* a concerted mechanism, in which the initial C–H activation is interrupted by a Cope rearrangement. Notably, the use of hexane as solvent was required to achieve high asymmetric induction, but this thesis will discuss the use of dichloromethane in highly asymmetric combined C–H functionalization/Cope rearrangement with the new chiral dirhodium catalyst.



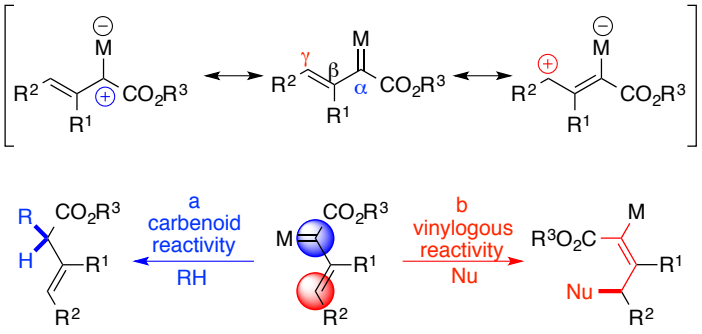
Scheme 1.5 The initial discovery on CHCR

As for the mechanist insights, it was proposed that the carbenoid-induced C–H functionalization proceeds through a concerted but highly asynchronous transition state from previous kinetic isotope effect study.[26] A more recent study that combined experimental and theoretical observations provided a detailed picture of C–H insertion

transition state.[30] The calculation suggested a considerable amount of hydride shift character. A partial positive charge at the carbon in the substrate is built up in the transition state; therefore, substrates that can stabilize the positive charge will be more reactive and this is consistent with previous experimental observation (KIE values).

1.3.3 Vinylogous transformation of rhodium vinylcarbenes

The development of novel transformations of rhodium vinylcarbenes is a current research area of intense interest. In addition to the normal carbenoid reactivity, one impressive feature of these intermediates is vinylogous reactivity (Scheme 1.6). Some early studies on this uncommon reactivity that date back to 20 years ago by the Davies group has enabled the very recent resurgence of many innovative and catalytic vinylogous transformations of transient metallovinylcarbenes, in which a diverse range of unique products are made possible in intermolecular fashion. Importantly, the development of new methods and catalysts to control the selective vinylogous reactivity over the carbenic site transformation would be expected to have a transformative effect on metallocarbene chemistry. One major theme of this thesis is to create novel vinylogous transformations of rhodium vinylcarbenes and detailed discussions on the background will be included in later chapters.



Scheme 1.6 General reactivity of metallovinylcarbene

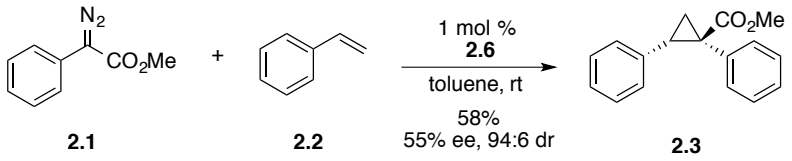
Simply put, this thesis covers new chiral dirhodium catalyst development and reaction discovery in the following areas: (i) exploration and design of dirhodium phosphonate catalysts in combination with donor/acceptor diazoacetates, with particular discussions of the role of donor groups in asymmetric induction; (ii) development of novel dirhodium triarylcyclopropane carboxylate catalysts, with discussions of the unique bulky feature of the catalyst in terms of previous problem-solving; (iii) application of the steric crowded catalysts in intramolecular cyclopropantion of α-allyl rhodium carbenes; (vi) Influence of bulky catalysts on the configuration of rhodium vinylcarbenes and enhancement of vinylogous transformations; Attempted application of bulky dirhodium catalysts to vinylogous fluorination and discovery of alternative silver catalyzed process; (v) impact of bulky catalysts on site selective intermolecular C-H functionalizations.

Chapter II

Exploration of D_4-Symmetric Dirhodium Tetraphosphonates as Catalysts for Donor/Acceptor Carbenoid Reactions

2.1 Introduction

The study and design of dirhodium tetraphosphonate catalysts has been a long-standing project in the Davies group. The overall complex of this type of catalyst would have a D_4-symmetry due to the rigid C_2-symmetry of the ligands, which would be an ideal class of dirhodium catalyst for carbene transformations. Previously, the Davies group concentrated on testing the the designed dirhodium phosphonate catalysts in the reaction of methyl phenyldiazoacetate (**2.1**) with styrene (**2.2**).[31] In the Davies group, Dr. Li designed and synthesized a variety of dirhodium phosphonate catalysts and the major catalysts are summarized (Figure 2.1). Among the catalysts examined, the best enantioselectivity in the reaction was obtained with the new dirhodium catalyst (**2.6**), providing the cyclopropane (**2.3**) in 55% ee (Scheme 2.1). The limited success by catalyst design for the model reaction led us to re-think this chemistry. Since the phosphonate ligands contain many aromatic rings, we wonder whether the π-π interactions between these ligands and the aromatic donor group of the carbene at the rhodium carbene formation stage would give new possibilities for achieving highly asymmetric carbene transformations. To test this idea, we initiated a project to study the effects of the donor groups in dirhodium phosphonate catalyzed carbene reactions.



Scheme 2.1 Optimal result in previous dirhodium phosphonate-catalyzed reactions

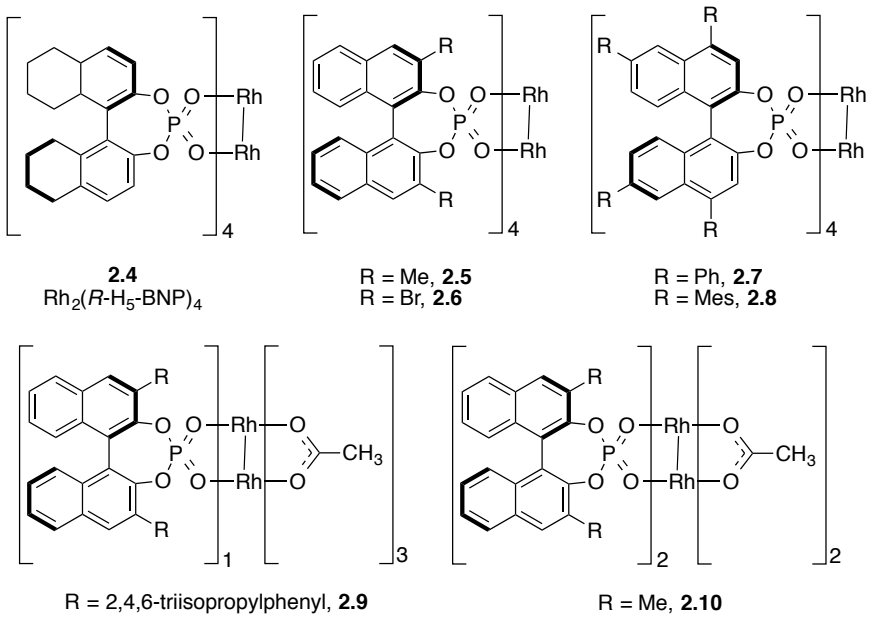
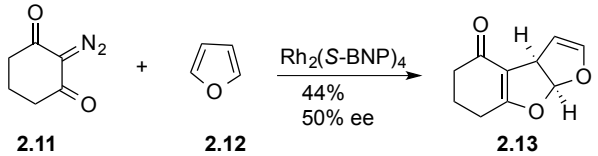


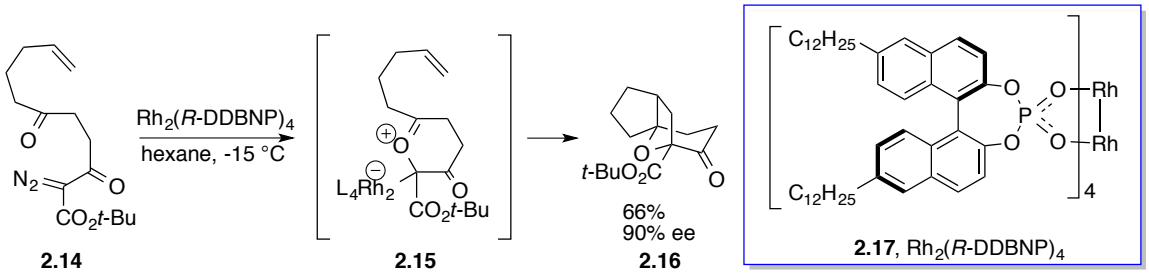
Figure 2.1 Representative dirhodium phosphonate catalysts from Dr. Li

The most significant previous carbene ransformations with chiral dirhodium phosphonate catalysts are summarized below. The initial study with this catalyst was used in the asymmetric dipolar cycloaddition reaction between 2-diazocyclohexane-1,3-dione (**2.11**) with furan (**2.12**), which provided the bicyclic product (**2.13**) in 44% yield and 50% ee [32] (Scheme 2.13).



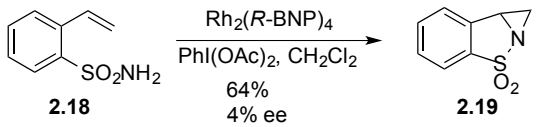
Scheme 2.2 Rh_2(*S*-BNP)$_4$-catalyzed reaction with furan

Later, Hodgson and co-workers synthesized a variety of binaphthylphosphate catalysts and evaluated their reactivity and selectivity in a dipolar cycloaddition reaction.[21] Among the catalysts examined, Rh_2(*R*-DDBNP)$_4$ with *n*-dodecyl chain at 6,6'-positions gave the optimal result in the intramolecular ylide formation/cycloaddition reaction of diazoacetoacetate (**2.14**) (Scheme 2.3). The tricyclic product (**2.16**) was isolated in 66% yield and 90% ee.[21c]

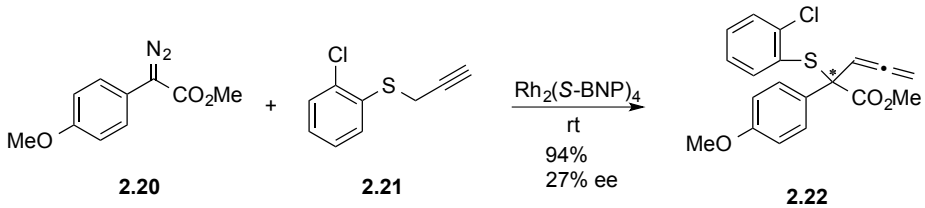


Scheme 2.3 Rh_2(*R*-DDBNP)$_4$-catalyzed 1,3-dipolar cycloaddition

In many other reactions studied, however, these catalysts had very limited success. For example, Rh_2(*R*-BNP)$_4$-catalyzed intramolecular aziridination of sulfonamide (**2.18**) produced (**2.19**) in 64% yield and 4% ee (Scheme 2.4);[33] Rh_2(*S*-BNP)$_4$-catalyzed reaction of *p*-methoxyphenyldiazoacetate (**2.20**) and sulfide (**2.21**) gave the sulfur ylide/[2,3]-sigmatropic rearrangement product (**2.22**) in 94% yield, but only 27% ee[34] (Scheme 2.5).

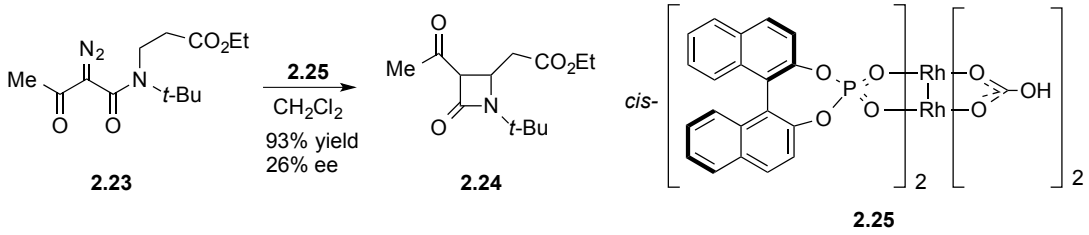


Scheme 2.4 Rh_2(*R*-BNP)$_4$-catalyzed intramolecular aziridination



Scheme 2.5 Rh_2(*S*-BNP)$_4$-catalyzed [2,3]-sigmatropic rearrangement

The study on dirhodium complex with mixed binaphthylphosphate ligands has been limited to Rh_2(*S*-BNP)$_2$(HCO_3)$_2$ (**2.25**).[35] The intramolecular C–H insertion of diazo (**2.23**) with complex (**2.25**) as catalyst produced compound (**2.24**) in 93% yield and 26% ee (Scheme 2.6).

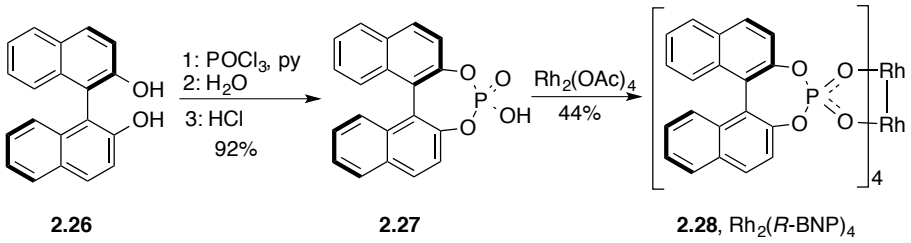


Scheme 2.6 Rh_2(*S*-BNP)$_2$(HCO_3)$_2$-catalyzed intramolecular C–H insertion

2.2 Results and discussion

2.2.1 Synthesis of Rh_2(*R*-BNP)$_4$

As summarized in Scheme 2.7, the synthetic route begins with commercially available, enantiomerically pure *R*-binaphthol (**2.26**).[21c] The desired phosphoric acid (**2.27**) was obtained in 92% isolated yield as an off-white powder by a one-pot, three-step procedure: (1) heating with phosphoryl trichloride in pyridine at 90 °C for 90 min; (2) addition of water and heating for another 90 min; (3) acidifying the system with 6 N HCl at 90 °C for another 90 min. A final ligand exchange reaction between (**2.27**) and $Rh_2(OAc)_4$ in refluxing chlorobenzene afforded the catalyst (**2.28**) in 44% yield. The ^{1}H NMR spectral data of the catalyst are consistent with previous reported results,[31] and was used in the following study.



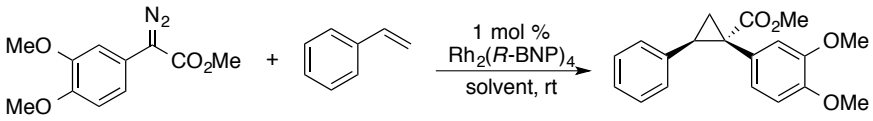
2.26 **2.27** **2.28**, Rh_2(*R*-BNP)$_4$

Scheme 2.7 The synthetic route of Rh_2(*R*-BNP)$_4$

2.2.2: Rh_2(*R*-BNP)$_4$-catalyzed cyclopropanation

Initial studies of the reaction conditions were conducted by using Rh_2(*R*-BNP)$_4$ as the catalyst, and the reaction between methyl 2-diazo-2-(3,4-dimethoxyphenyl)acetate (**2.29**) and styrene (**2.2**) as the model reaction. Since solvents play important roles in dirhodium catalyzed asymmetric cyclopropanation reactions,[8b] solvent effects in Rh_2(*R*-BNP)$_4$-catalyzed cyclopropanation were first examined. The results are summarized in Table 2.1.

Table 2.1 Solvent effects in Rh_2(*R*-BNP)$_4$-catalyzed cyclopropanation



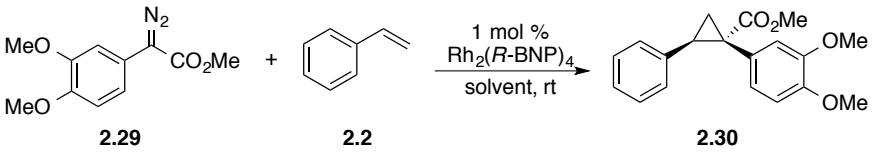
2.29 **2.2** **2.30**

entry	solvent	yield (%)[b]	ee (%)[c]
1	toluene	93	94
2	DCM	72	86
3	$PhCF_3$	65	88
4	tol/hex (5/1)	67	88

Among the solvents screened, toluene was the optimal solvent, affording the cyclopropane product (**2.30**) in 93% isolated yield and 94% ee. In the Rh_2(*S*-DOSP)$_4$-catalyzed cyclopropanation of styrene, the solvent effects had great influence on the enantioselectivity, for example, the use of dichloromethane instead of pentane or hexane dramatically decreased the enantioselectivity from 92% to 79% ee in cyclopropanation of styrene,[8b] which suggested the non-polar hydrocarbon solvent could reduce the

possibility of conformational change of ligands on Rh_2(*S*-DOSP)$_4$. When Rh_2(*R*-BNP)$_4$ was employed, however, the solvents did not have dramatic influence on enantioselectivity, probably because of the limited conformational mobility of Rh_2(*R*-BNP)$_4$.

Table 2.2 Catalyst loading in Rh_2(*R*-BNP)$_4$-catalyzed cyclopropanation



2.29 **2.2** **2.30**

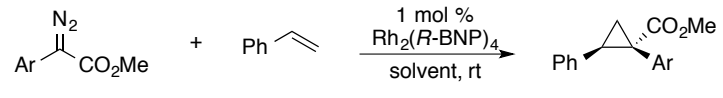
entry	cat. loading (mol %)	time (h)	yield (%)	ee (%)
1	1.0	1.5	93	94
2	0.1	12	80	93
3	0.01	17	73	40

The effects of catalyst loadings on the reactivity and selectivity of the cyclopropanation reaction were then explored. The results are summarized in Table 2.2. As seen from Table 2, Rh_2(*R*-BNP)$_4$ was still an effective catalyst when catalyst loading was decreased to 0.1 mol% (Table 2.2, entry 2), providing the desired product (**2.30**) in 80% isolated yield and 93% ee. Further decreasing the loading of catalyst, however, led to a great drop in enantioselectivity (Table 2.2, entry 3).

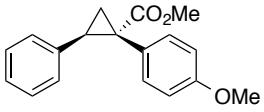
Next, the scope of Rh_2(*R*-BNP)$_4$ catalyzed cyclopropanation was examined by decomposition of various diazo compounds in the presence of styrene (Table 2.3). All the reactions catalyzed by Rh_2(*R*-BNP)$_4$ went smoothly and provided the cyclopropanes in yields ranged from 40% to 93%, but the enantioselectivity was very sensitive to electronic and steric effects of substrates. In contrast to the 3,4-dimethoxyphenyl-derived product (**2.30**), the *para*-methoxyphenyl-derived cyclopropane (**2.32a**) was obtained in

84% isolated yield and 57% ee. The *ortho*-methoxyphenyl-derived cyclopropane (**2.32b**) was

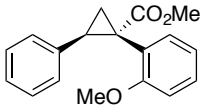
Table 2.3 Scope of Rh_2(*R*-BNP)$_4$-catalyzed cyclopropanation



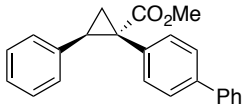
2.31a-o **2.2** **2.32a-o**



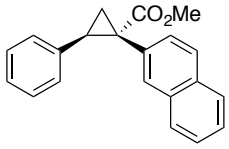
2.32a
84%
57% ee



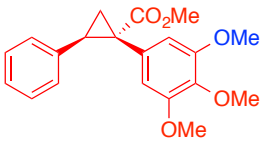
2.32b
69%
27% ee



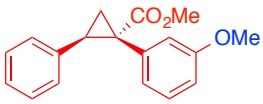
2.32c
81%
59% ee



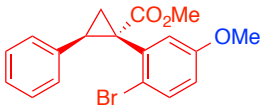
2.32d
94%
59% ee



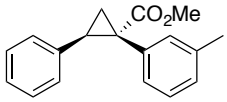
2.32e
63%
90% ee



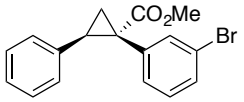
2.32f
82%
88% ee



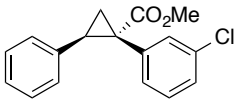
2.32g
44%
82% ee



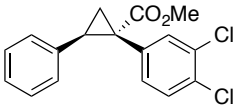
2.32h
51%
42% ee



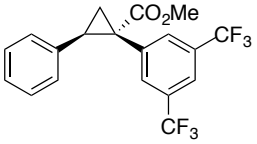
2.32i
70%
58% ee



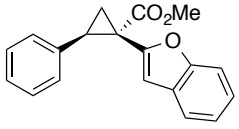
2.32j
67%
50% ee



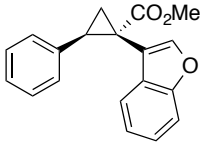
2.32k
82%
63% ee



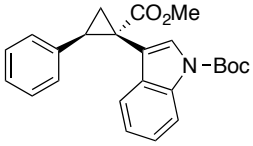
2.32l
57%
37% ee



2.32m
67%
50% ee



2.32n
70%
69% ee

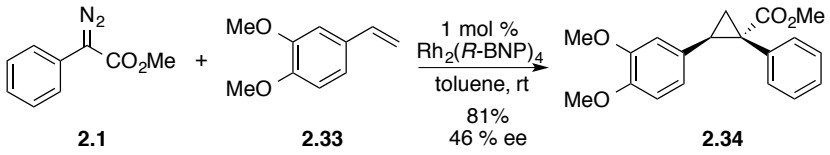


2.32o
83%
84% ee

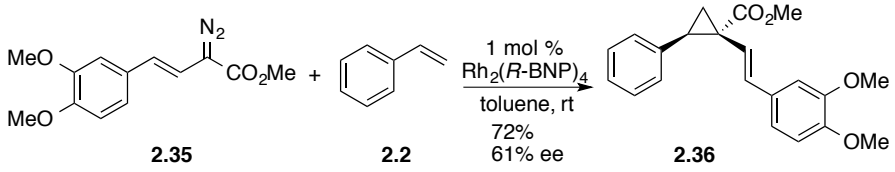
obtained in much lower enantioselectivity (27% ee). This large difference in enantioselectivity among these products led us to evaluate the effects of *meta*-substituents

on asymmetric induction in this cyclopropanation reaction. Among the *meta*-substituents examined, the *meta*-methoxy substituent was crucial for high enantioinduction. When the aromatic donor groups have the *meta*-methoxy group, the asymmetric induction is routinely high as can be seen from products (**2.32e-g**). However, other *meta*-substituents such as methyl, bromo, chloro, and trifluoromethyl on the aryl group failed to afford high enantioselectivity in the products. Examination of diazo compounds bearing hetero-aromatic donor groups was also conducted. The indole derived cyclopropane product (**2.32o**) was obtained in higher enantioselectivity than the benzofuran derived products (**2.32m-n**). The use of 3,4-dimethoxyphenyl as a donor group played a crucial role in Rh_2(*R*-BNP)$_4$-catalyzed cyclopropanation reaction; it might suggest that the *pi*-stacking effects between 3,4-dimethoxyphenyl group and the ligand were the reason for high asymmetric induction.

We also examined the reaction between phenyldiazoacetate (**2.1**) and 3,4-dimethoxystyrene (**2.33**) (Scheme 2.8). The cyclopropane product **2.34** was isolated in 81% yield and 46% ee.



Scheme 2.8 Cyclopropanation of 3,4-dimethoxystyrene



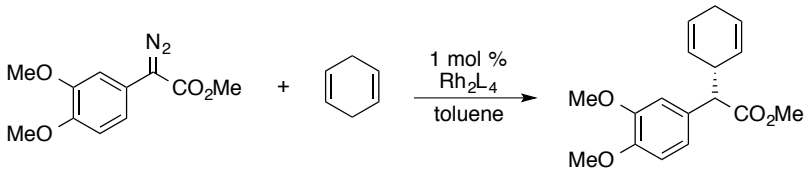
Scheme 2.9 Reaction of 3,4-dimethoxystyryldiazoacetate with styrene

Next, we examined the length of the donor group by use of vinyldiazoacetate (**2.35**). As seen in Scheme 2.9, Rh_2(*R*-BNP)$_4$ catalyzed cyclopropanation reaction between vinyl diazoacetate (**2.35**) and styrene (**2.2**) gave cyclopropane product (**2.36**) in 72% yield and 61% ee.

2.2.3: Rh_2(*R*-BNP)$_4$-catalyzed C–H functionalization

To evaluate the ability for Rh_2(*R*-BNP)$_4$-catalyzed C–H functionalization, we chose the model reaction between diazo (**2.29**) and cyclohexa-1,4-diene (**2.37**) using 1 mol% catalyst loading of Rh_2(*R*-BNP)$_4$. The Rh_2(*S*-DOSP)$_4$ was also examined as control experiment. The results are summarized in Table 2.4. The desired product (**2.38**) was isolated in 76% yield and 65% ee using Rh_2(*S*-DOSP)$_4$., but a better enantioselectivity in 78% ee was obtained by use of Rh_2(*R*-BNP)$_4$ (Table 2.4, entry 2). Lowering the temperature from room temperature to 0 ^{o}C did not improve the enantioselectivity (Table 2.4, entry 3).

Table 2.4 Rh(II)-catalyzed C–H functionalization of cyclohexa-1,4-diene

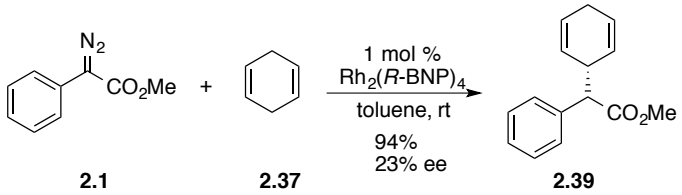


2.29 **2.37** **2.38**

entry	catalyst	temp. (°C)	yield (%)	ee (%)
1	Rh_2(*S*-DOSP)$_4$	23	76	-65
2	Rh_2(*R*-BNP)$_4$	23	59	78
3	Rh_2(*R*-BNP)$_4$	0	57	76

The enantioselectivity was still substrate-dependent in Rh_2(*R*-BNP)$_4$ catalyzed C–H insertion reactions. For example, when methyl phenyl diazo acetate (**2.1**) was used in the

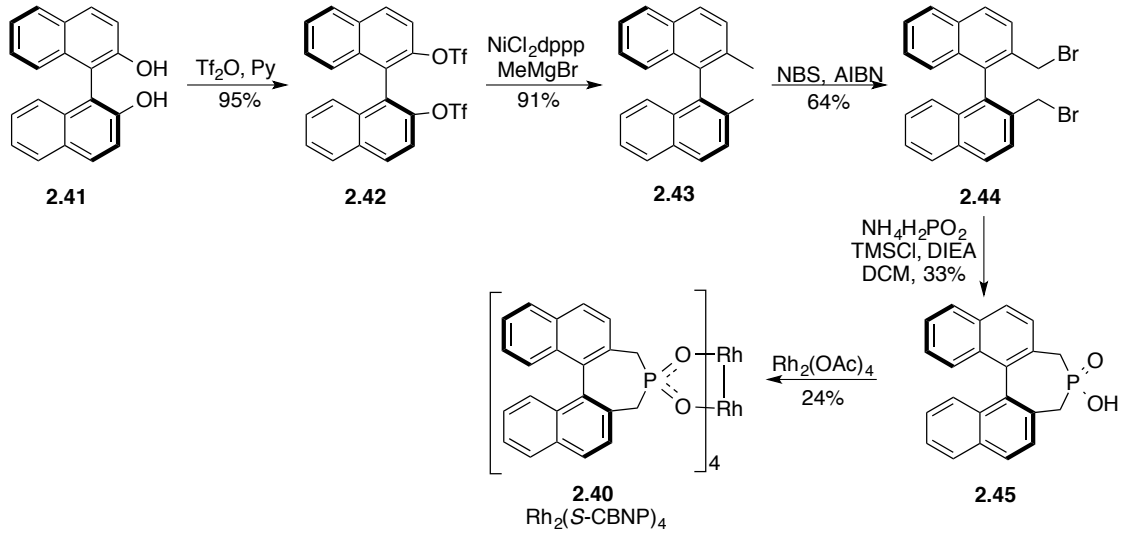
reaction with cyclohexa-1,4-diene (**2.37**), product (**2.39**) was isolated in 94% yield and 23% ee (Scheme 2.10).



Scheme 2.10 Reaction of methyl phenyldiazoacetate with cyclohexa-1,4-diene

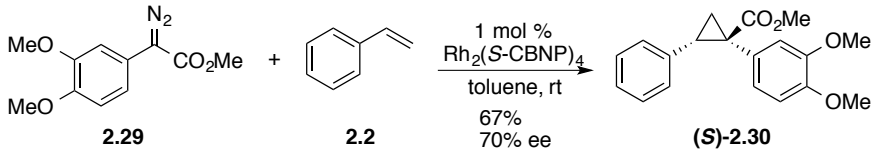
2.3.4: Rh_2(*S*-CBNP)$_4$: design, synthesis and evaluation

Since the solvent and conformational structure of catalyst was crucial for asymmetric induction, a new dirhodium binaphthylphosphonate catalyst Rh_2(*R*-CBNP)$_4$ (**2.40**) was designed (Scheme 2.11). The displacement of oxygen with a methylene group not only could increase solubility of this catalyst in hydrocarbon solvents; but the conformational structure of this catalyst would be altered. We wondered how these changes could affect the asymmetric induction in metallocarbene chemistry.

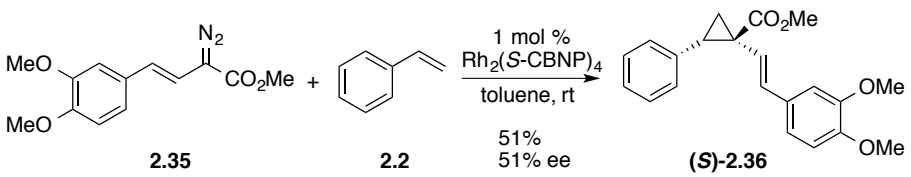


Scheme 2.11 Synthetic routes towards Rh_2(*S*-CBNP)$_4$

As shown in Scheme 2.7, the synthetic route toward product (**2.40**) was followed by a known procedure.[36] The *S*-binaphthalene triflate (**2.41**) was obtained in 92% isolated yield by protection of *S*-BINOL with triflic anhydride. Ni-catalyzed cross-coupling reaction between (**2.42**) and methyl magnesium bromide afforded (*S*)-2,2'-dimethyl-1,1'-binaphthalene (**2.43**) in 91% yield, and then a radical bromination reaction provided the bis(bromomethyl)-1,1'-binaphthalene (**2.44**) in 64% yield. A ring closure reaction provided the acid **(2.45**) in 33% yield, and a final ligand exchange between (**2.45**) and $Rh_2(OAc)_4$ afforded the product (**2.40**) in 24% yield. The product (**2.40**) was characterized by ^1H NMR, ^{13}C NMR, Infrared methods, the characterization with mass spectroscopy using either APCI or ESI ion source led to several fragmentation peaks and a molecular ion peak has not been determined at this stage; then, with this material in hand, we first examined its reactivity and selectivity in the standard cyclopropanation. The reaction between methyl 2-diazo-2-(3,4-dimethoxyphenyl)acetate (**2.29**) and styrene (**2.2**) was re-examined with this new catalyst. The reaction resulted in the enantiomer of product (**2.30**) in 67% isolated yield and 70% ee (Scheme 2.12). In the reaction between diazo (**2.35**) and styrene (**2.2**), the reaction gave the enantiomer of product (**2.36**) in 51% isolated yield and 51% ee (Scheme 2.13). From these results, Rh_2(*S*-CBNP)$_4$ gave much lower enantioinduction than that of Rh_2(*R*-BNP)$_4$ in cyclopropanation reactions.



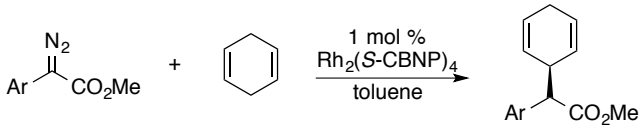
Scheme 2.12 Evaluation of Rh_2(*S*-CBNP)$_4$ in cyclopropanation with aryldiazoacetate

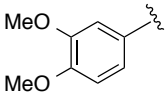
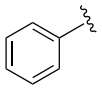
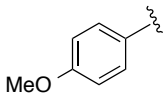


Scheme 2.13 Evaluation of Rh_2(*S*-CBNP)$_4$ in cyclopropanation with styryldiazoacetate

Rh_2(*S*-CBNP)$_4$ catalyzed C–H insertion reactions were also examined (Table 2.5). The Rh_2(*S*-CBNP)$_4$ catalyzed C–H insertion reaction produced the enantiomer of product (**2.38**) in 89% ee (Table 2.5, entry 1), which was the highest enantioselectivity among the catalysts examined. However, the asymmetric induction with this new catalyst was still substrate-dependent. When diazo (**2.1**) and (**2.31a**) were used, low enantioselectivity in the products were observed (Table 2.5, entries 2-3).

Table 2.5 Rh_2(*S*-CBNP)$_4$ -catalyzed C–H functionalization of cyclohexa-1,4-diene



entry	Ar	diazo	prod.	yield (%)	ee (%)
1		**2.29**	**(*S*)-2.38**	42	89
2		**2.1**	**(*S*)-2.39**	62	42
3		**2.31a**	**2.46**	49	26

2.3 Conclusion

The Rh_2(*R*-BNP)$_4$-catalyzed asymmetric cyclopropanations with styrenes was examined with a diverse range of donor/acceptor diazoacetates. The study indicated that the efficiency of these reactions was good as reasonable yields were routinely obtained;

the asymmetric induction of these reactions was not very sensitive to solvents but it was dependent on the type of donor group used. The use of a *meta*-methoxy aryl ring as a donor group was found to be crucial to achieve high asymmetric induction (up to 94% ee); otherwise, low to moderate enantioselectivity in the cyclopropanation was observed with a diverse range of aryl or heteroaryl as the donor groups on aryldiazoacetates. The Rh_2(*R*-BNP)$_4$-catalyzed asymmetric C–H functionalization reactions were also examined with the 3,4-dimethoxyphenyldiazoacetate being the optimal carbene precursor and cyclohexa-1,4-diene as the active C–H substrate; however, this reaction gave lower asymmetric induction than the corresponding reaction with Rh_2(*R*-DOSP)$_4$ as a catalyst.

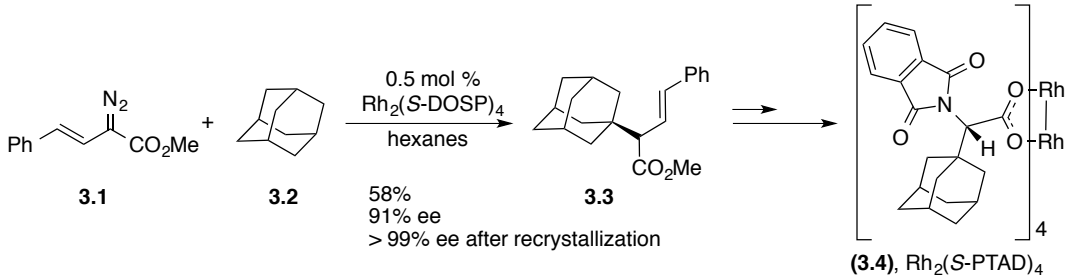
A new dirhodium phosponate catalyst Rh_2(*S*-CBNP)$_4$ was also designed and synthesized. The study with this novel catalyst indicated that it was not an effective chiral catalyst for cyclopropanation since a lower asymmetric induction in 70% ee was obtained compared with the 94% ee obtained with Rh_2(*R*-BNP)$_4$. Interestingly, it was found to be the optimal catalyst for C–H functionalization of cyclohexa-1,4-diene in the presence of 3,4-dimethoxyphenyldiazoacetate, providing the product in 89% ee, which was the best result among all the catalysts examined. Future study should be directed to design analogs of Rh_2(*S*-CBNP)$_4$ catalyst to achieve more selective C–H functionalization.

Chapter III

Development of Sterically Hindered D_2-Symmetric Dirhodium Catalyst Derived from Cyclopropane Carboxylate Ligands: Design, Synthesis and Initial Evaluation

3.1 Introduction

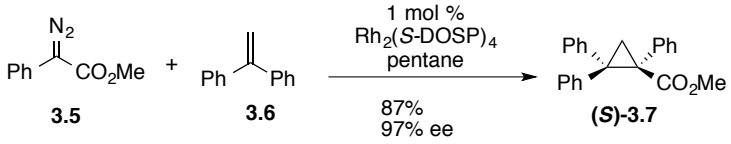
The use of enantioselective carbene transformations as key steps in complex targets synthesis has emerged as attractive strategies.[37] Particularly attractive is the concept that the Rh_2(*S*-DOSP)$_4$-catalyzed enantioselective reactions could be used as a foundation for the generation of new chiral catalysts. One example is the use of enantioselective C–H functionalization for the synthesis of Rh_2(*S*-PTAD)$_4$[15] (Scheme 3.1). The key step is the reaction of the styryldiazoacetate (**3.1**) with adamantane (**3.2)** to generate the C-H functionalization product (**3.3**) in 91 % ee, which then could be converted to the amino acid ligand required for the formation of Rh_2(*S*-PTAD)$_4$ (**3.4**).



Scheme 3.1 C–H insertion of adamantane as a key step in Rh_2(*S*-PTAD)$_4$ synthesis

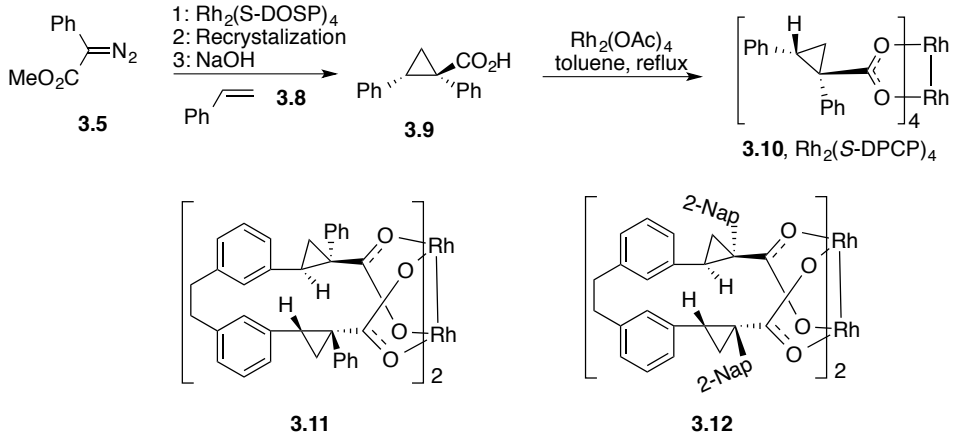
Another very efficient Rh_2(*S*-DOSP)$_4$-catalyzed reaction is the cyclopropanation reaction between phenyldiazoacetate (**3.5**) and 1,1-diphenylethylene (**3.6**), which

generated the triarylcyclopropane ester (*S*)-**3.7** in 97% ee[22] (Scheme 3.2). Therefore, we became intrigued with the possibility that this reaction could be used as a foundation for the generation of a new class of bulky catalysts.

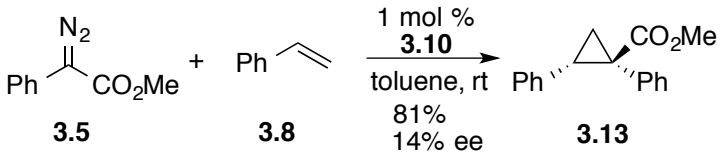


Scheme 3.2 Rh_2(*S*-DOSP)$_4$-catalyzed highly enantioselective cyclopropanation

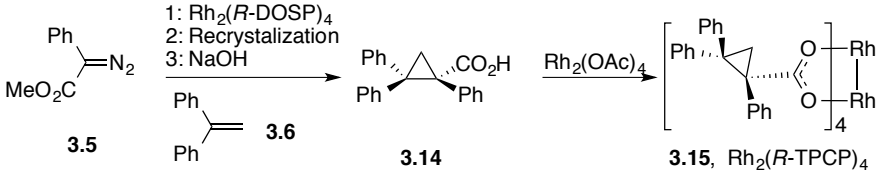
In the Davies group, Dr. Thompson first synthesized some dirhodium diarylcyclopropane carboxylate catalysts[38] (Scheme 3.3). It started with the Rh_2(*S*-DOSP)$_4$-catalyzed enantioselective cyclopropanation between phenyldiazoacetate (**3.5**) and styrene (**3.8**), followed by recrystallization and sodium hydroxide promoted hydrolysis as well as ligand exchange with rhodium acetate in refluxing toluene, affording the dirhodium catalyst (**3.10**) Rh_2(*S*-DPCP)$_4$. A similar strategy was used to synthesize two bridged dirhodium cyclopropane carboxylate catalyst (**3.11**) and (**3.12**) depending on the aryl group used on the diazoacetate.



Scheme 3.3 Thompson's cyclopropane-based catalyst synthesis

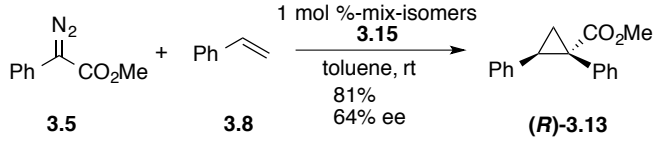


Scheme 3.4 Thompson's optimal cyclopropanation results



Scheme 3.5 Hansen's synthesis of Rh_2(*R*-TPCP)$_4$

Among these catalysts evaluated, the Rh_2(*S*-DPCP)$_4$ catalyzed cyclopropanation reaction of phenyldiazoacetate (**3.5**) and styrene (**3.8**) gave cyclopropane product (**3.13**) in 14% ee as the highest enantioselectivity (Scheme 3.4). Dr. Hansen then proposed that a substituent in a *syn*-relationship to the carboxylate group on the ligand would enhance the selectivity.[39] Dr. Hansen tried to synthesize the dirhodium tetrakis(triarylcyclopropane) carboxylate complex Rh_2(*R*-TPCP)$_4$, followed by a similar procedure as reported by Dr. Thompson (Scheme 3.5), but the synthetic method gave a mixture of inseparable isomeric rhodium complexes (**3.14**); the evaluation of the catalyst mixture in the cyclopropanation reaction resulted in the cyclopropane (***R***)-**3.13** in 81% yield and 64% ee[39] (Scheme 3.6).



Scheme 3.6 Hansen's evaluation of isomers Rh_2(*R*-TPCP)$_4$

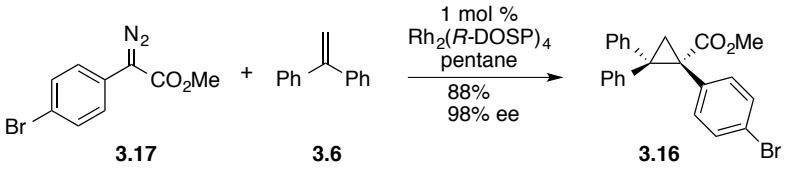
In this chapter, we will describe the successful generation of the pure dirhodium cyclopropane triarylcarboxylate catalyst. Furthermore, we will showcase the tolerance and efficiency of the new catalyst in asymmetric carbene transformations and also

rationalize the observed stereochemical outcome by means of analysis of the structure from X-ray crystallography and computational studies.

3.2 Results and discussion

3.2.1 Dirhodium cyclopropane carboxylate catalysts: synthesis and evaluation

The triarylcyclopropane ester (**3.16**) was chosen as a candidate because it was assumed that the bromo functional group could help recrystallization in a late-stage purification of catalyst. The Rh_2(*R*-DOSP)$_4$ catalyzed cyclopropanation reactions between *para*-bromophenyl diazoacetate (**3.17**) and 1,1-diphenylethylene (**3.6**) provided the cyclopropane (**3.16**) in 88% yield and 98% ee (Scheme 3.7).



Scheme 3.7 The synthesis of triarylcyclopropane ester

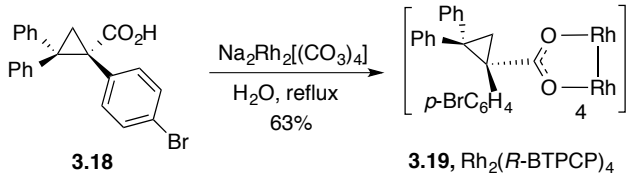
Table 3.1 Hydrolysis of triarylcyclopropane ester

entry	base	solvent	yield (%)
1	NaOH	THF/H_2O = 1/$_1$	<5
2	NaOH	Dioxane/H_2O = 1/$_1$	<5
3	NaOH	MeOH/H_2O = 1/$_1$	<5
4	KOH	MeOH/H_2O = 1/$_1$	<5
5	LiOH	MeOH/H_2O = 1/$_1$	<5
6[a]	KOBu-*t*	DMSO	68

[a] Reaction was conducted at room temperature.

The conversion of the cyclopropane ester (**3.16**) was initially examined by use of general base in several different solvents at refluxing conditions, no evident hydrolyzed product (**3.18**) was observed from crude NMR analysis and the ester was recovered

(Table 3.1, entries 1-5). The use of potassium *tert*-butoxide in dimethyl sulfoxide at room temperature was the optimal condition for the hydrolysis, affording the carboxylic acid product (**3.18**) in 64% yield after careful acidification of the reaction with 1.0 N HCl. The enantiopurity of cyclopropane carboxylic acid was further enriched to >99% ee by recrystallization. Considering the ligand exchange between triarylcyclopropane carboxylic acid and rhodium acetate in refluxing chlorobenzene resulted in isomeric mixtures of catalyst in Dr, Hansen's exploratory studies,[39] an alternative method with rhodium sodium carbonate was examined in refluxing water. This method generated the catalyst, Rh_2(*R*-BTPCP)$_4$, (**3.19**) as a green solid in 63% isolated yield (Scheme 3.8). No isomer of catalyst was observed from ^{1}H NMR analysis and the crystal structure of this catalyst was determined by X-ray crystallography (Figure 3.1), which indicates the D_2-symmetric structure of this catalyst.



3.18 **3.19,** Rh_2(*R*-BTPCP)$_4$

Scheme 3.8 The synthesis of Rh_2(*R*-BTPCP)$_4$ catalyst

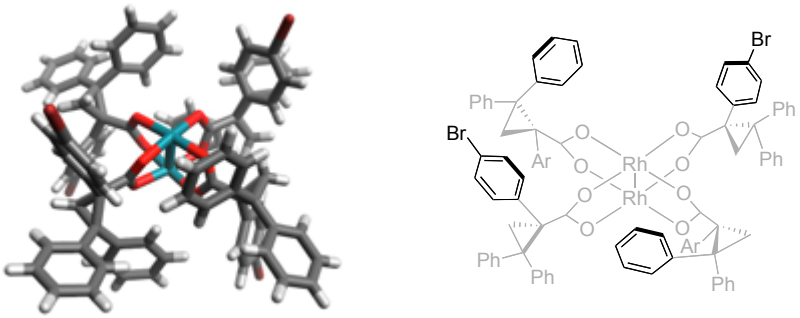
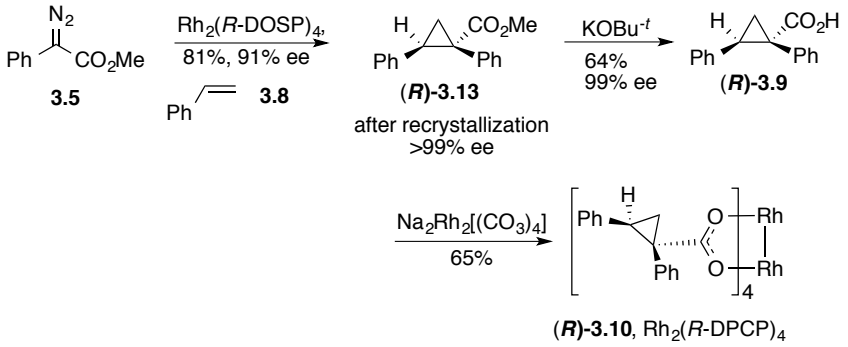


Figure 3.1 X-ray crystal structure of Rh_2(*R*-BTPCP)$_4$

According to this general method, a variety of dirhodium cyclopropane carboxylate catalysts were synthesized as a single isomer. The synthesis of the diphenylcyclopropane

carboxylate catalyst was re-examined (Scheme 3.9). The Rh_2(*R*-DOSP)$_4$-catalyzed cyclopropanation between phenyldiazoacetate (**3.5**) and styrene (**3.6**) gave the cyclopropane (***R*-3.13**) in 81% isolated yield and 91% ee, which was further enriched to > 99% ee by recrystallization. Ligand exchange with rhodium sodium carbonate provided the catalyst (***R*-3.10**) in 65% isolated yield.

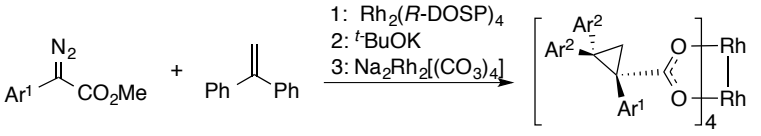


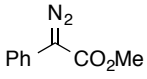
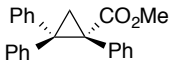
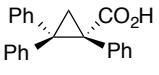
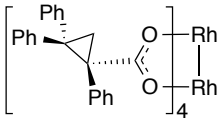
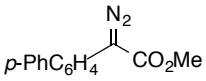
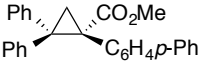
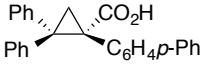
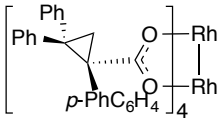
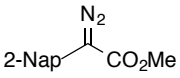
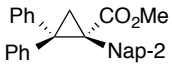
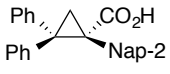
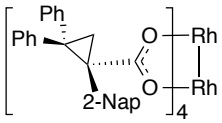
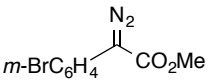
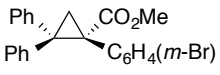
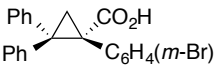
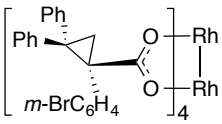
Scheme 3.9 The synthesis of Rh_2(*R*-DPCP)$_4$ catalyst

The synthesis of triphenylcyclopropane carboxylate catalyst (**3.15**) was re-examined (Table 3.2, entry 1). As expected, the cyclopropanation and hydrolysis step proceeded smoothly to afford the triphenylcyclopropane carboxylic acid (**3.14**) and recrystallization was used to enrich the enantiopurity to >99% ee. The ligand exchange with rhodium sodium carbonate afforded the catalyst (**3.15**) in 68% isolated yield. It should be noted that no isomeric mixture of the triphenylcyclopropane carboxylate catalyst (**3.15**) was observed from ^{1}H NMR analysis. This new procedure was applied to the synthesis of some other analogs of triarylcyclopropane carboxylate catalysts with different electronic and steric properties (Table 3.2, entries 2-4). For example, the biphenyl-derived cyclopropane ester (**3.21**) was obtained in 84 % yield and > 99 % ee, which underwent hydrolysis and ligand exchange to afford the catalyst (**3.23**) in 65% isolated yield (Table 3.2, entry 2). The 2-naphthyl-derived cyclopropane ester (**3.25**) was synthesized in 74 %

isolated yield and > 99% ee, the hydrolysis step provided the corresponding carboxylic acid (**3.26**) in 61% isolated yield and the ligand exchange gave the catalyst (**3.27**) in 58% isolated yield (Table 3.2, entry 3). The *meta*-bromophenyl-derived cyclopropane ester (**3.29**) was synthesized in 93% isolated yield and > 99% ee, the hydrolysis step provided the corresponding carboxylic acid (**3.30**) in 79% isolated yield and the ligand exchange gave the catalyst (**3.31**) in 58% isolated yield (Table 3.2, entry 4).

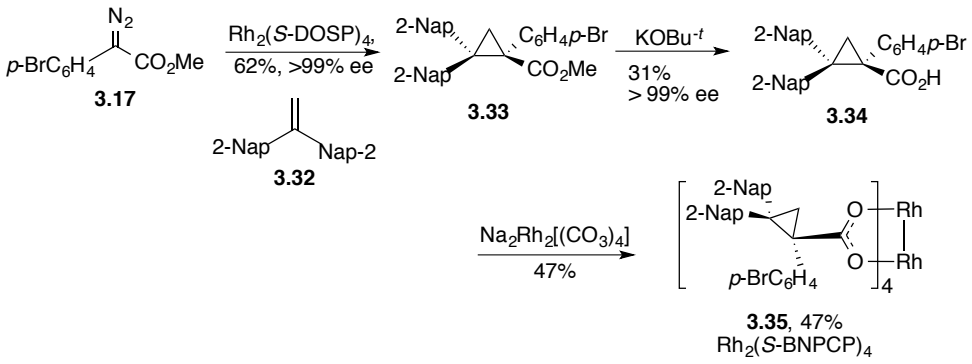
Table 3.2 Examples of dirhodium triarylcyclopropane carboxylate catalysts



entry	diazo compound	cyclopropane ester	cyclopropane acid	dirhodium catalyst
1				
	3.5	***R*-3.7**, 82% 99% ee	**3.14**, 55% 99% ee	**3.15,** 68% Rh_2(*R*-TPCP)$_4$
2				
	3.20	**3.21**, 84% > 99% ee	**3.22**, 70% > 99% ee	**3.23,** 65% Rh_2(*R*-BPCP)$_4$
3				
	3.24	**3.25**, 74% > 99% ee	**3.26**, 61% > 99% ee	**3.27**, 58% Rh_2(*R*-NPCP)$_4$
4				
	3.28	**3.29**, 93% > 99% ee	**3.30**, 79% > 99% ee	**3.31**, 62% Rh_2(*R*-MBTPCP)$_4$

To examine the effect of the aryl ring from 1,1-diarylethylene, the 2,2'-(ethene-1,1-diyl)dinaphthalene (**3.32**) was used in combination with aryldiazoacetate (**3.17**), affording

the cyclopropane (**3.33**) in 62% isolated yield and 98 % ee and was enriched to >99% ee after recrystallization. Followed by hydrolysis and ligand exchange, the catalyst (**3.35**) was obtained in 47 % isolated yield (Scheme 3.10).



Scheme 3.10 The synthesis of Rh_2(*S*-BNPCP)$_4$ catalyst

To alter the electronic property of catalyst, some electron-rich and electron-poor donor group was used in the cyclopropanation reaction and the ligands are summarized in Figure 3.2. For example, the *para*-methoxyphenyl-derived cyclopropane (**3.36**) was obtained in 73% isolated yield and 99% ee, and subsequent hydrolysis gave the corresponding carboxylic acid (**3.37**) in 56% isolated yield without erosion the enantioselectivity. However, the ligand exchange between *para*-methoxyphenyl derived ligand (**3.37**) and rhodium sodium carbonate in refluxing water caused the formation of isomers in the reaction from the analysis of the ^{1}H NMR (there are four sets of dd peaks from 1.8-2.8 ppm), and only a small amount (<15 mg) relatively pure product can be obtained from purification on silica gel column at this stage. No further efforts were taken to synthesize this catalyst. As for the electron-poor ligand, the *para*-nitrophenyl-derived cyclopropane ester (**3.38**) was obtained in 93% isolated yield and 94% ee. The hydrolysis step is problematic not only because the yield was low (34% isolated yield) but also because the racemization eroded the enantiopurity in the product (**3.39**, 0% ee).

The reason why the racemization happened could be that the electron-deficient *para*-nitrophenyl stabilized the carbanion generated from ring opening under base condition followed by ring-closure. The 3,5-ditrifluoromethylphenyl derived cyclopropane ester (**3.40**) was synthesized in 92% yield and 37% ee. Considering the racemization process in the *para*-nitrophenyl-derived system, no further efforts were taken at this stage to enrich this ligand. The *ortho*-bromophenyl derived ligand (3.42) was obtained in 59% yield and >99% ee, but the ligand exchange afford a mixture of isomers due to the hindered ligand; the use of 1-naphthyl-derived cyclopropane carboxylic acid (**3.44**) led to a sluggish ligand exchange with rhodium sodium carbonate, and no definitive catalyst was isolated from this reaction..

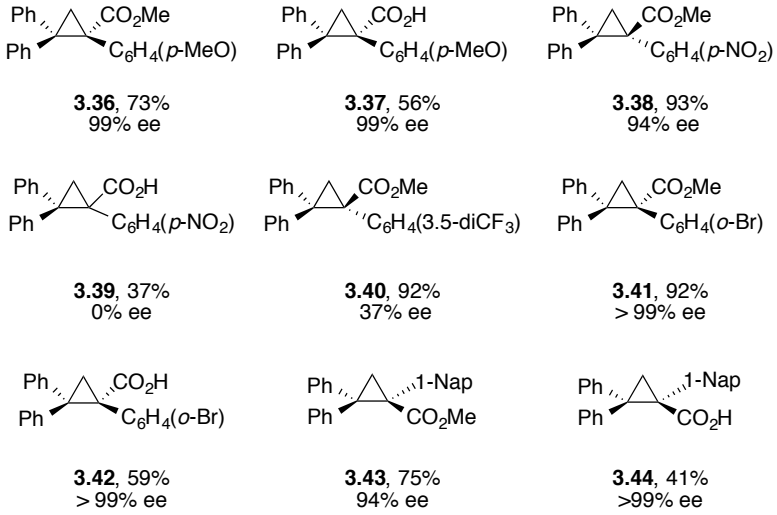
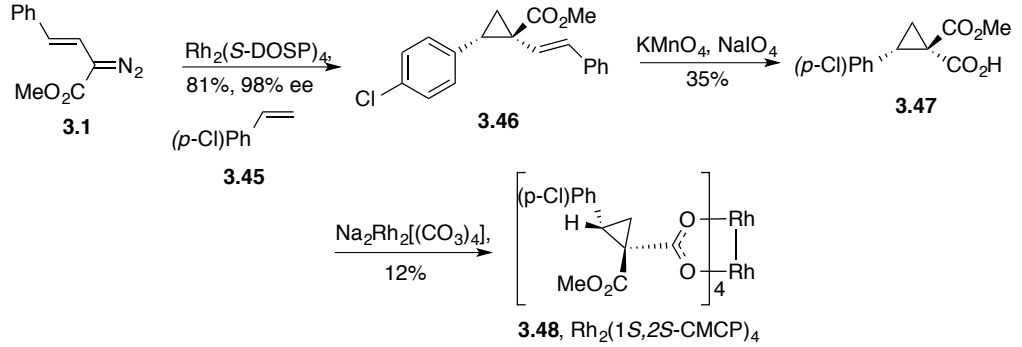


Figure 3.2 The ligands library for potential dirhodium catalysts

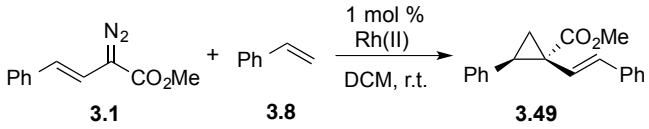
A new dirhodium cyclopropane carboxylate (**3.48**) was also synthesized using an alternative approach. It began with Rh_2(*R*-DOSP)$_4$-catalyzed cyclopropanation reaction between methyl styryldiazoacetate (**3.1**) and 1-chloro-4-vinylbenzene (**3.45**), affording the cyclopropane (**3.46**) in 81% isolated yield and 98% ee. The subsequent oxidation

cleavage of the alkene afforded the carboxylic acid (**3.47**) in 35% isolated yield, which underwent ligand exchange to afford the catalyst (**3.48**) in 12% yield (Scheme 3.11).



Scheme 3.11 The synthetic routes towards Rh_2(1*S*,2*S*-CMCP)$_4$

Table 3.3 Evaluation of dirhodium cyclopropane carboxylate in cyclopropanation



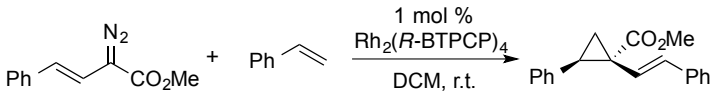
entry	catalyst	yield (%)	ee (%)
1	Rh_2(*R*-DPCP)$_4$	81	11
2	Rh_2(1*S*,2*S*-CMCP)$_4$	81	22
3	Rh_2(*R*-TPCP)$_4$	84	79
4	Rh_2(*R*-BTPCP)$_4$	86	91
5	Rh_2(*R*-NPCP)$_4$	77	94
6	Rh_2(*R*-BPCP)$_4$	76	84
7	Rh_2(*S*-BNPCP)$_4$	74	-87

With these catalysts in hand, we examined their reactivity and selectivity in the standard reaction between the styryldiazoacetate (**3.1**) and styrene (**3.8**). In contrast to the results obtained with Rh_2(*R*-DPCP)$_4$, Rh_2(*1S,2S*-CMCP)$_4$ improves the enantioselectivity to 22% ee while keeping high reactivity (Table 3.3, entry 2). The use of triphenylcyclopropane carboxylic acid derived catalyst Rh_2(*R*-TPCP)$_4$ further enhances the enantioselectivity to 79% ee (Table 3.3, entry 3). The enantioselectivity was greatly increased over 90% ee when Rh_2(*R*-BTPCP)$_4$ or Rh_2(*R*-NPCP)$_4$ was used as a catalyst

(Table 3.3, entries 5-6). Increasing the size of the aryl group that has a *syn*-relationship with carboxylate from phenyl to 2-naphthyl did not show great improvement in asymmetric induction (Table 3.3, entry 7).

To further optimize this reaction, we then examined the solvent and catalyst loading as well as temperature effects on Rh_2(*R*-BTPCP)$_4$-catalyzed cyclopropanation reaction. The results that were compared with Rh_2(*R*-DOSP)$_4$ as a catalyst and are summarized in Table 3.4.

Table 3.4 Optimization studies on Rh(II)-catalyzed cyclopropanation[a]



3.1 **3.8** **3.49**

entry	solvent	temp. (°C)	time (h)	Rh_2(*R*-BTPCP)$_4$		Rh_2(*R*-DOSP)$_4$	
				yield (%)	ee (%)	yield (%)	ee (%)
1	CH_2Cl_2	23	1.5	86	91	80	81
2	CH_2Cl_2	0	2.0	72	91	81	84
3	CH_2Cl_2	-78	12	71	91	78	87
4[b]	CH_2Cl_2	23	24	77	92	69	81
5[c]	CH_2Cl_2	23	60	46	92	38	81
6	pentane	23	1.5	82	89[d]	85	92
7	toluene	23	1.5	84	88	80	90
8	diethyl Ether	23	1.5	88	87	85	90
9	ethyl acetate	23	1.5	79	91	81	90
10	acetone	23	1.5	78	93	82	87
11	DMF	23	24	13	95	5	85
12	DMSO	23	24	8	85	--	--

[a] To Rh_2(*R*-BTPCP)$_4$ (7.0 mg) and styrene (2.0 mmol) at given temperature in 1.0 mL of given solvent was added a solution of **3.1** (0.4 mmol) in 2.0 mL of given solvent over 1 h. Isolated yields, > 20/1 dr. [b] 0.1 mol% catalyst. [c] 0.01 mol% catalyst. [d]under Rh_2(*S*-BTPCP)$_4$

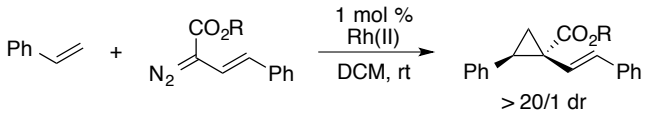
The Rh_2(*R*-BTPCP)$_4$-catalyzed reaction can routinely give high enantioselectivity in dichloromethane (91-92% ee), which is better than the corresponding Rh_2(*R*-DOSP)$_4$-catalyzed reactions. Temperature did not influence the enantioselectivity of the Rh_2(*R*-BTPCP)$_4$-catalyzed reaction between diazo (**3.1**) and styrene (**3.8**) as cyclopropane (**3.49**)

was produced in 91% ee over a reaction temperature range from 23 to -78 °C (Table 3.4, entries 1-3). Furthermore, decreasing the catalyst loading to 0.1 mol % and even 0.01 mol % did not alter the enantioselectivity (Table 3.4, entries 4-5), but the reaction did not go fully to completion at the 0.01 mol % catalyst loading. Rh_2(*R*-DOSP)$_4$ did slightly better in solvents such as pentane, toluene and diethyl ether in asymmetric induction (Table 3.4, entries 6-8). Surprisingly, both catalysts could give high asymmetric induction in polar solvents like acetone, ethyl acetate. The use of DMF and DMSO inhibits the reaction, but the enantioselectivity still remained very high when Rh_2(*R*-BTPCP)$_4$ was used as catalyst (Table 3.4, entries 11-12). Overall, Rh_2(*R*-BTPCP)$_4$ gave higher asymmetric induction than Rh_2(*R*-DOSP)$_4$ when dichloromethane was used as solvent but Rh_2(*R*-DOSP)$_4$ performed better than expected in a range of other polar solvents, and so, the two catalysts performed similarly in these solvents.

3.2.2 Scope of Rh_2(*R*-BTPCP)$_4$-catalyzed carbenoid reaction

High asymmetric induction with Rh_2(*R*-DOSP)$_4$ can only be obtained when the electron-withdrawing group is a methyl ester. Even changing the methyl ester to a *tert*-butyl ester caused a dramatic drop in the enantioselectivity[8b]. Therefore, a study was undertaken to determine how Rh_2(*R*-BTPCP)$_4$-catalyzed reactions responded to the size of the ester (Table 3.5). Rh_2(*R*-BTPCP)$_4$ exhibited good tolerance to ester size, and the enantioselectivity actually improved on increasing the ester size from methyl to *tert*-butyl (Table 3.5, entries 1-4, from 91% ee to 95% ee). In contrast, hindered esters were confirmed to have a detrimental effect on asymmetric induction with Rh_2(*R*-DOSP)$_4$, leading to a steady drop in enantioselectivity from 81% ee to 16% ee (Table 3.5, entries, 5-8).

Table 3.5 The size of ester effects in Rh(II)-catalyzed cyclopropanation

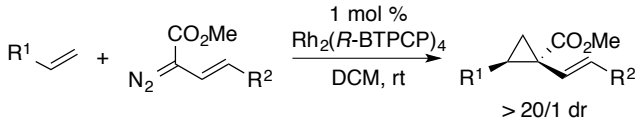


entry	starting diazol	R	catalyst	product	yield(%)	ee
1	**3.1**	Me	Rh_2(*R*-BTPCP)$_4$	**3.49**	86	91
2	**3.50**	Et	Rh_2(*R*-BTPCP)$_4$	**3.53**	88	93
3	**3.51**	^{i}Pr	Rh_2(*R*-BTPCP)$_4$	**3.54**	89	96
4	**3.52**	^{t}Bu	Rh_2(*R*-BTPCP)$_4$	**3.55**	87	95
5	**3.1**	Me	Rh_2(*R*-DOSP)$_4$	**3.49**	80	81
6	**3.50**	Et	Rh_2(*R*-DOSP)$_4$	**3.53**	84	75
7	**3.51**	^{i}Pr	Rh_2(*R*-DOSP)$_4$	**3.54**	82	55
8	**3.52**	^{t}Bu	Rh_2(*R*-DOSP)$_4$	**3.55**	80	16

To probe the generality of this catalyst in enantioselective cyclopropanation with donor/acceptor carbenoid intermediates, various combinations of aryl- or vinyldiazoacetates and terminal alkenes were evaluated. The results for representative vinyldiazoacetates and terminal alkenes are summarized in Table 3.6. All the reactions proceeded smoothly in dichloromethane, affording the corresponding cyclopropanes with high diastereo- and enantioselectivity with yields ranging from 59% to 94%. Donor groups with electron-donating substituents favored the asymmetric induction compared with those having electron-withdrawing substituents. Electron-deficient alkenes gave better enantioselectivity than electron-rich olefins. For example, *para*-trifluoromethylstyrene reacted with styryldiazoacetate, producing the desired cyclopropane (**3.67**) in 97% ee (Table 3.6, entry 1) while *para*-methoxystyrene produced the corresponding cyclopropane (**3.70**) in 84% ee at room temperature, but with 93% ee at -40 °C (Table 3.6, entry 5). Inclusion of an *ortho* substituent on the styrene had little

influence on enantioselectivity, as reaction of *ortho*-methylstyrene and methyl 2-vinylbenzoate with diazo (**3.1**) provided

Table 3.6 Rh_2(*R*-BTPCP)$_4$-catalyzed cyclopropanation with vinyl diazoacetates[a]



entry	R^1	alkene	R^2	diazo	prod	yield (%)	ee (%)[b]
1	*p*-$CF_3C_6H_4$	**3.56**	C_6H_5	**3.1**	**3.67**	87	97
2	*p*-$NO_2C_6H_4$	**3.57**	C_6H_5	**3.1**	**3.68**	92	95
3	*p*-ClC_6H_4	**3.45**	C_6H_5	**3.1**	**(*R*)-3.46**	86	95
4	*3,4*-diClC_6H_3	**3.58**	C_6H_5	**3.1**	**3.69**	88	93
5	*p*-$MeOC_6H_4$	**3.59**	C_6H_5	**3.1**	**3.70**	94	84(93)[c]
6	*o*-MeC_6H_4	**3.60**	C_6H_5	**3.1**	**3.71**	88	93
7	*o*-$CO_2MeC_6H_4$	**3.61**	C_6H_5	**3.1**	**3.72**	59	89
8	n-Bu	**3.62**	C_6H_5	**3.1**	**3.73**	60	90
9	C_6H_5	**3.8**	*p*-ClC_6H_4	**3.63**	**3.74**	82	90
10	C_6H_5	**3.8**	*3,4*-diClC_6H_3	**3.64**	**3.75**	79	86
11	C_6H_5	**3.8**	*3,4*-di$MeOC_6H_3$	**3.65**	**3.76**	70	-93[d]
12	C_6H_5	**3.8**	Me	**3.66**	**3.77**	17	46

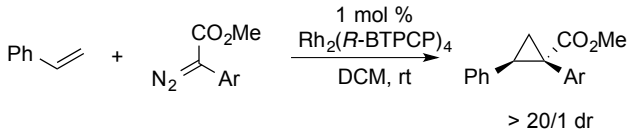
[a]The reaction was conducted with Rh_2(*R*-BTPCP)$_4$ (7.0 mg, 0.0004 mmol), alkene (2.0 mmol, 5.0 equiv.), diazoester (0.4 mmol, 1.0 equiv.) at 23 °C in dichloromethane under argon unless otherwise stated. [b] ee was abtained by HPLC analysis. [c] Temperature at -40 °C. [d] Rh_2(*S*-BTPCP)$_4$ was used.

the cyclopropanes (**3.71**) and (**3.72**) in 93% ee and 89% ee, respectively (Table 3.6, entries 6, 7). Non-activated alkenes are also suitable substrates as 1-hexene gave the cyclopropane (**3.73**) in 60% yield and 90% ee (Table 3.6, entry 8). The low enantioselectivity was observed when methyl (*E*)-2-diazopent-3-enoate (**3.66**) was used, providing the cyclopropane (**3.77**) in 46% ee (Table 3.6, entry 12). The low yield in this reaction was probably due to the catalyst poison from pyrazole formation during the reaction.[8b]

The cyclopropanation reactions of representative aryldiazoacetates are summarized in Table 3.7. The reactions generated the corresponding cyclopropanes in high yield and

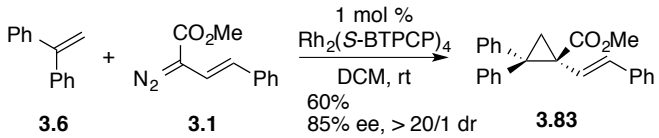
stereoselectivity (>20:1 dr, 83-91% ee), with *p*-methoxyphenyl derivative giving the highest enantioselectivity (Table 3.7, entry 3). These results are similar to the reported results for the Rh_2(*S*-DOSP)$_4$-catalyzed cyclopropanations of aryldiazoacetates in hexane as solvent.[4b]

Table 3.7 Rh_2(*R*-BTPCP)$_4$-catalyzed cyclopropanation with aryl diazoacetates

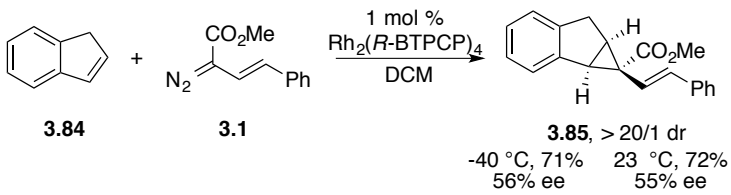


entry	Ar	diazo	prod	yield (%)	ee (%)
1	C_6H_4	**3.5**	***R*-3.13**	82	83
2	*p*-BrC_6H_4	**3.17**	**3.80**	80	85
3	*p*-$MeOC_6H_4$	**3.78**	**3.81**	74	91
4	*p*-$CF_3C_6H_4$	**3.79**	**3.82**	86	89

The Rh_2(*S*-BTPCP)$_4$ catalyzed cyclopropanation of 1,1-diphenylethylene (**3.6**) upon decomposition of diazo (**3.1**) led to cyclopropane (**3.83**) in 60% yield and 85% ee (Scheme 3.12). In the previous report, Rh_2(*S*-bi-TISP)$_2$ could catalyzed this reaction, affording the product (3.83) in 94% yield and 91% ee.[4c] When indene (**3.84**) was used in the cyclopropanation reaction, cyclopropane (**3.85**) was formed in 72% yield and 55% ee at room temperature; further lowering the temperature did not improve the selectivity of this reaction (Scheme 3.13).

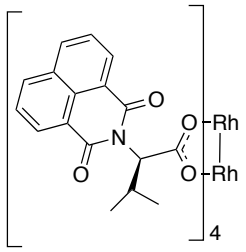


Scheme 3.12 Rh_2(*S*-BTPCP)$_4$-catalyzed cyclopropanation of 1,1-diphenylethylene

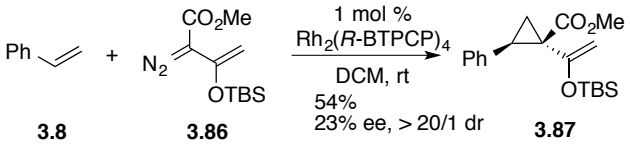


Scheme 3.13 Rh_2(*R*-BTPCP)$_4$-catalyzed cyclopropanation of indene

The reaction between siloxyvinyl diazoacetate (**3.86**) and styrene (**3.5**) was also examined. The cyclopropane (**3.87**) was isolated in 54% yield and 23% ee (Scheme 3.14). The absolute configuration of product (**3.87**) was assigned by analogy with previous results in this chapter. As comparison, Múller and co-workers have reported that Rh_2(*R*-ntv)$_4$ (**3.88**) was found to be an effective catalyst to generate the enantiomer of (**3.87**) in 94% ee.[40]



3.88, Rh_2(*R*-NTV)$_4$

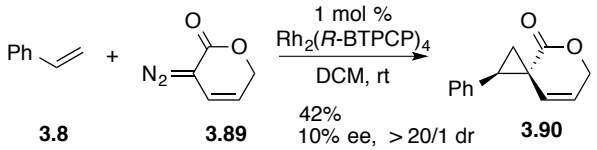


3.8 **3.86** **3.87**

Scheme 3.14 Cyclopropanation with siloxylvinyldiazoacetate

The unsaturated diazolactone (**3.89**) was not a good substrate in Rh_2(*R*-BTPCP)$_4$-catalyzed cyclopropanation, leading to the formation of spiro cyclopropane (**3.90**) in 42% yield and 10% ee (Scheme 3.15). The absolute configuration of product (**3.90**) was assigned by analogy with previous results in this chapter. As comparison, Doyle and co-workers have reported that the carboxamidate Rh_2(*S*,*R*-menthAZ)$_4$ was capable of generating the spiro compound (**3.90**) in 74% yield and 84% ee in > 20:1 diastereoselectivity; [41] recently, Katsuki and co-workers have reported that a chiral

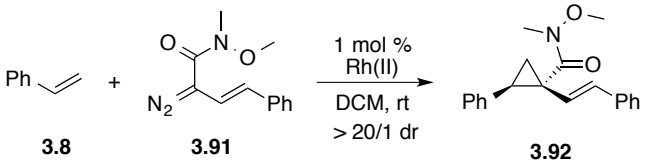
Ir(salen) complex can catalyzed this transformation effectively, leading to (**3.90**) in 94% yield and 99% ee as a single diastereomer.[42]



Scheme 3.15 Rh_2(*R*-BTPCP)$_4$-catalyzed cyclopropanation with diazolactone

To expand the scope of acceptor group, the use of styryldiazoamide (**3.91**) in dirhodium-catalyzed cyclopropanation of styrene was also studied and the results are summarized in Table 3.8. Among the catalysts examined, the newly developed dirhodium triarylcyclopropane carboxylate catalyst showed enhanced enantioselectivity than the well-established dirhodium catalysts. The Rh_2(*R*-NPCP)$_4$ is the optimal catalyst, delivering the product (**3.92**) in 91% ee. The yield of the cyclopropane product was not determined at this stage and a relatively pure ^{1}H NMR was obtained, but the cyclopropane (**3.92**) was not fully characterized because of the presence of an impurity. To overcome this issue, the phenyldiazoamide (**3.93**) was synthesized and evaluated in the cyclopropanation of styrene. The result indicated the cyclopropane amide (**3.94**) was produced in 45% yield and 89% ee as a pure compound (Scheme 3.16).

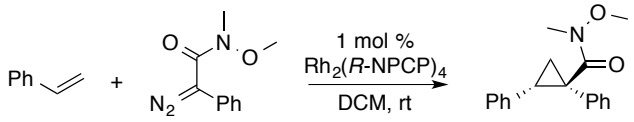
Table 3.8 Optimization on cyclopropanation with styryldiazoamides



3.8 **3.91** **3.92**

entry	catalyst	ee (%)
1	Rh_2(*R*-NPCP)$_4$	91
2	Rh_2(*R*-BTPCP)$_4$	79
3	Rh_2(*R*-BPCP)$_4$	79
4	Rh_2(*R*-DOSP)$_4$	33
5	Rh_2(*S*-PTAD)$_4$	58
7	Rh_2(*R*-BNP)$_4$	-21

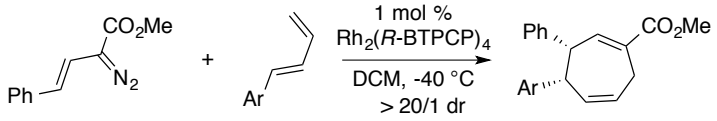
[a]The yield was not determined due to the formation of an impurity that was hard to separate from the desired product at that stage.



3.8 **3.93** **3.94**

Scheme 3.16 Rh_2(*R*-NPCP)$_4$-catalyzed cyclopropanation with phenyldiazoamide

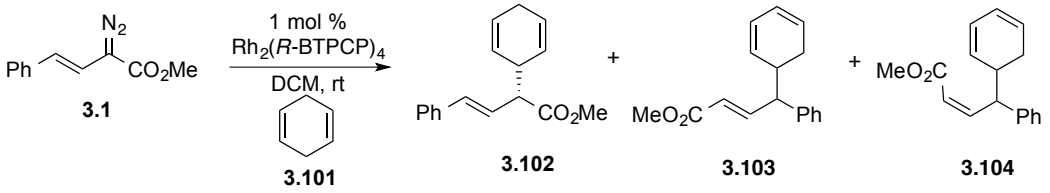
Table 3.9 Rh_2(*R*-BTPCP)$_4$ catalyzed tandem cyclopropanation/Cope rearrangement



entry	Ar	diene	prod	yield (%)	ee (%)
1	C_6H_4	**3.95**	**3.98**	56	87
2	*p*-$CF_3C_6H_4$	**3.96**	**3.99**	71	91
3	*p*-$MeOC_6H_4$	**3.97**	**3.100**	60	89

Encouraged by the cyclopropanation results, we decided to investigate the scope of the catalyst further by looking at more elaborate reactions of vinyldiazoacetates. When vinyldiazoacetates react with dienes, a formal [4 + 3] cycloaddition occurs by a tandem cyclopropanation/Cope rearrangement.[23] The Rh_2(*R*-BTPCP)$_4$-catalyzed reactions of styryldiazoacetate (**3.1**) with dienes gave rise to the cycloheptadienes in 56-71% yields

(Table 3.9). As is typical of this transformation, cycloheptadienes were formed as single diastereomers and the enantioselectvity ranged from 87-91% ee.

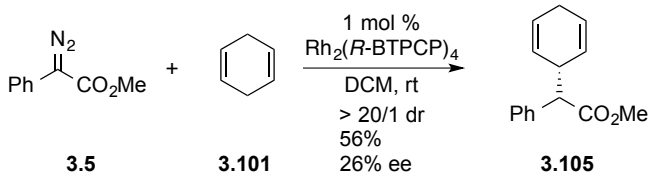


Scheme 3.17 Rh_2(*R*-BTPCP)$_4$-catalyzed C–H insertion with styryl diazoacetate

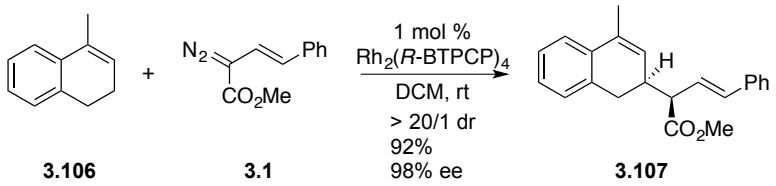
In recent years, vinyl diazoacetates have been shown to be broadly useful in a range of C–H functionalization reactions.[28] An initial study was conducted on the reaction between 1,4-cyclohexadiene (**3.101**) and styryldiazoacetate **(3.1**). When the reaction was conducted with Rh_2(*R*-BTPCP)$_4$ in dichloromethane at room temperature, the reaction resulted in a mixture of the direct C-H functionalization and the combined C-H functionalization/Cope rearrangement products (**3.102**/**3.103**/**3.104** = 60/31/9, 8% ee for product **3.102**, dr > 20:1). In a previous report,[43] when Rh_2(*S*-DOSP)$_4$ was used in 2,2-dimethylbutane at room temperature, the reaction gave a complex mixture of direct C-H functionalization product and the combined C-H functionalization/Cope rearrangement (**3.102**/**3.103**/**3.104** = 26/72/2, 85% ee for product **3.102**, dr > 20:1).[43] The selectivity switch from the combined C-H functionalization/Cope rearrangement to direct C-H insertion with Rh_2(*R*-BTPCP)$_4$ was interesting but the enantioselectivity was low (Scheme 3.17).

In terms of the reaction between methyl phenyldiazoacetate (**3.5**) and 1,4-cyclohexadiene (**3.101)**, the use of Rh_2(*R*-BTPCP)$_4$ as catalyst gave the C-H functionalization product (**3.105**) in 56% yield and 26% ee; however, the Rh_2(*S*-DOSP)$_4$-

catalyzed reaction could afford the product (**3.105**) in 96% yield and 81% ee under solvent-free conditions.[44]



Scheme 3.18 Rh_2(*R*-BTPCP)$_4$-catalyzed C–H insertion with phenyl diazoacetate



Scheme 3.19 Rh_2(*R*-BTPCP)$_4$-catalyzed combined C–H insertion/Cope rearrangement

An impressive example is the formal C–H functionalization of dihydronaphthalene (**3.106**) to form (**3.107**). This reaction proceeds by a sequence involving a combined C–H functionalization/Cope rearrangement followed by a reverse Cope rearrangement. When this reaction was catalyzed by use of Rh_2(*R*-BTPCP)$_4$, the product (**3.107**) was formed in 92% yield as a single diastereomer and in 98% ee (Scheme 3.19), which absolute configuration was assigned by comparison with previous HPLC conditions. [45]This result compares favorably to the Rh_2(*S*-DOSP)$_4$-catalyzed formation of (**3.107**) with hexane as solvent.[45]

3.2.3 Computational modeling and stereoselectivity rationale

Developing predictive models for chiral dirhodium catalysts to rationalize and predict the outcome of the stereoselective transformations has been an important goal in the Davies group.[16] In previous studies, we learned that even though most of the chiral carboxylate ligands have C_1 symmetry, the dirhodium tetracarboxylates could exist in

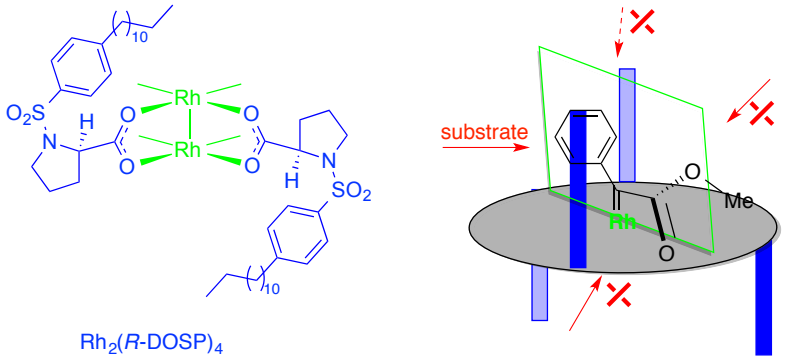


Figure 3.3 Proposed D_2-Symmetric $Rh_2(DOSP)_4$ and stereoselective model

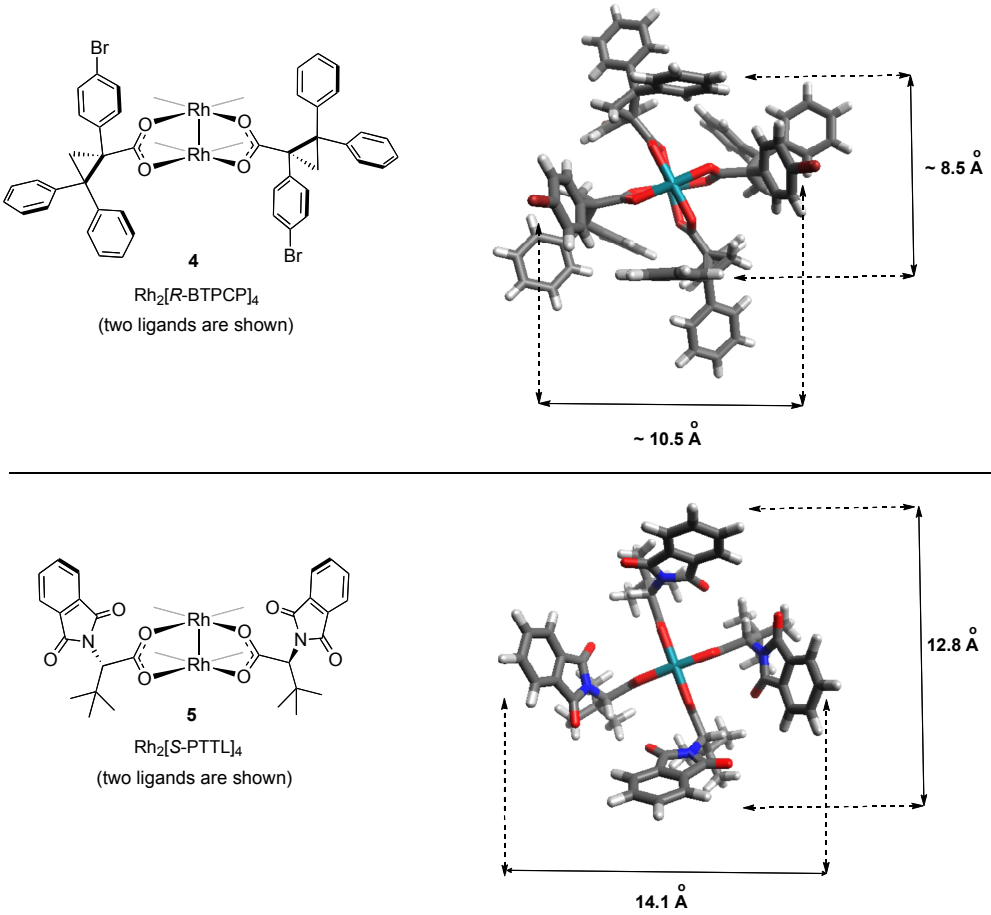


Figure 3.4 Size of $Rh_2(R\text{-BTPCP})_4$ and $Rh_2(S\text{-PTTL})_4$

conformations of higher symmetry than the ligands themselves.[2] In the previous study with $Rh_2(S\text{-DOSP})_4$ in hydrocarbon solvents, the enhancement of enantioselectivity has been proposed to be a result of solvent-influenced orientation of the prolinate ligands,

leading to a complex with D_2 symmetry.[8b] The four bulky sulfonyl ligands of Rh_2(*S*-DOSP)$_4$ exist in an "up-down-up-down" configuration, which allows the catalyst to define the approaching face of the substrate to the carbenoid, typically resulting in high asymmetric induction[8b] (Figure 3.3). Although no X-ray crystal information was obtained from Rh_2(*S*-DOSP)$_4$ to confirm the D_2 symmetrical conformation, this D_2 symmetric model served to rationalize the observed stereoselectivity in a variety of carbene transformations using this catalyst.[16]

As Rh_2(*R*-BTPCP)$_4$ is structurally quite different from Rh_2(*S*-DOSP)$_4$ catalyst, we want to understand how this catalyst controlled the asymmetric induction in carbene transformations. A single X-ray crystal of Rh_2(*R*-BTPCP)$_4$ was obtained (Figure 3.1). From the crystal analysis, the large chiral ligands of C_1 symmetry are organized in a D_2 symmetric arrangement, forming identical rectangular orthogonal (approx. 8.5 x 10.5 Å) binding cavities of C_2 symmetry at the two catalytically active axial termini of the rhodium dimer (Figure 3.4).

To rationalize the stereochemical outcome of the Rh_2(*R*-BTPCP)$_4$-catalyzed cyclopropanation, a computational modeling study was conducted by Dr. Boyarskikh. A summary of Dr. Boyarskikh's results is given here. Traditional computational approaches to analyze dirhodium carbene complexes have tended to rely on the X-ray structure of the catalyst in combination with DFT optimized geometries of the carbenoid with a simplified, achiral, catalyst model.[46] Although such analysis may provide preliminary insights into the catalyst selectivity, a more precise computational study has to account for interactions between the carbene and the ligands. The importance of such interactions was demonstrated by performing DFT calculations on the simplified model of the

catalyst-carbene complex (Figure 3.65. A comparison of the DFT optimized geometries with the size of the catalyst binding cavity revealed that even the shortest s-*trans* carbenoid conformation would not fit into the tight environment (the dimensions shown on Figures 3.5 and 3.6 were measured from atomic centers and do not account for atomic radii).

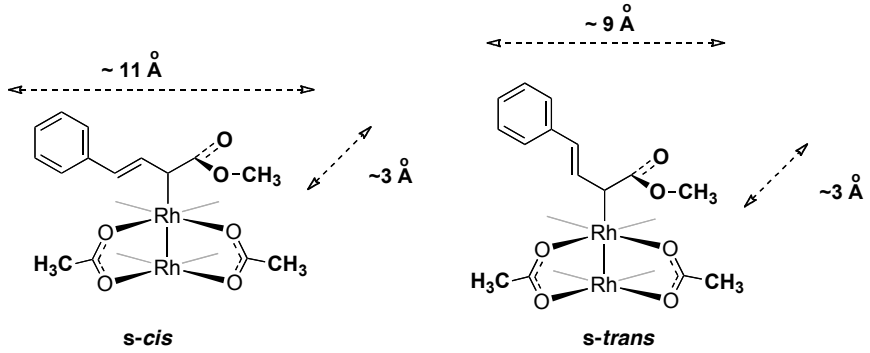


Figure 3.5 DFT model of *s-cis* and *s-trans* carbene conformers

Even though the dirhodium carboxylate ligands are capable of high asymmetric induction, this does not imply that the ligands are static and maintain the same arrangement through the entire catalytic cycle. Dr. Boyarskikh's DFT calculations suggested that steric interactions between the carbene and the ligands could result in a catalyst geometry different form the X-ray conformation. Therefore, it became imperative to conduct a computational study on the full catalyst-carbene system in order to investigate how the ligand arrangement was effected by the carbene. Performing DFT calculations on such a large (approx. 200 atoms) molecule would be limited to very small basis sets to be practical, and these may not give a realistic representation of the complex. Therefore, Dr. Boyarskikh's chose to employ an alternative approach. A two-layer ONIOM (QM:MM) method was used to divide the whole system into two subsystems (called the "model" and "real" layers) and each was calculated at the best possible level

of theory. The ONIOM partitioning of the catalyst-carbene system is shown in Figure 3.6. Hybrid DFT B3LYP and UFF methods were used for the calculations of the "model" (in red) and "real" (in blue) layers, respectively. Such partition provided an accurate description for the central rhodium carboxylate-carbene complex and accounted for the steric influence of the surrounding ligands.

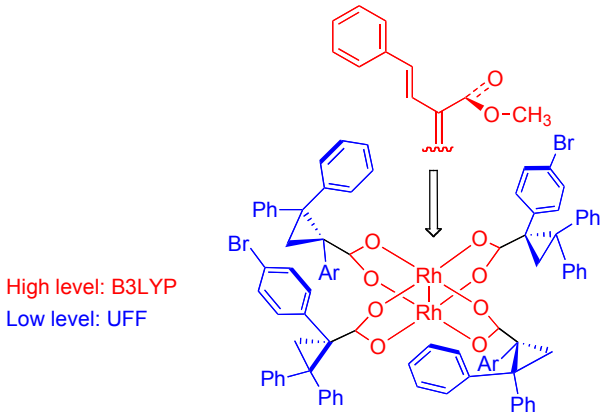


Figure 3.6 ONIOM partitioning scheme of Rh_2(*R*-BTPCP)$_4$-carbene complex

Dr. Boyarskikh's computational results supported the initial observations about the steric environment within the catalyst. Thus even the best matching combination of the shortest s-*trans* carbene aligned with the widest dimension of the orthogonal binding cavity caused steric repulsions significant enough to rotate two *para*-bromophenyl groups in either con- or dis-rotary directions. A similar result was obtained when the s-*trans* carbene was aligned with the shortest catalyst dimension; this time the phenyl groups rotated in a similar way. Overall, Dr. Boyarskikh was able to locate sixteen distinct minima on the potential energy surface corresponding to different conformations of the s-*trans* carbene with Rh_2(*R*-BTPCP)$_4$. The lowest energy conformation, separated from the closest one by 1.8 kcal/mol by total energy, is depicted in Figure 3.7. Two ligands rotated in a con-rotary fashion to minimize steric interactions with the carbene, whereas the other

two ligands remained in the upward position to reduce steric repulsions with the neighboring ligands. This arrangement resulted in a C_2 symmetric environment at the carbene site formed by the two-phenyl rings. One of the rings is blocking the donor group (aryl, styryl) while the other one is positioned next to the acceptor group (ester). The same ligand conformation having the *s-cis* carbene geometry was found to be 2.5 kcal/mol higher in energy.

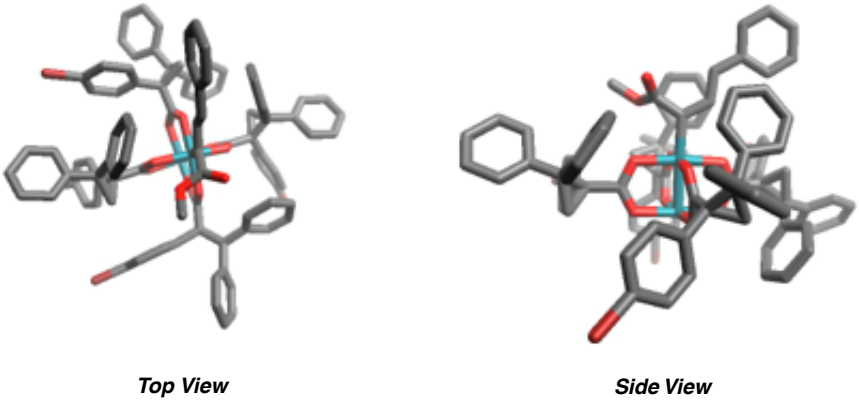


Figure 3.7 The lowest energy conformation of *s-trans* carbene

On the basis of the computational data summarized above, we propose a stereochemical model that explains the selectivity observed in Rh_2(*R*-BTPCP)$_4$ catalyzed transformations (Figure 3.8). It is well established that the substrate approaches donor/acceptor-substituted rhodium-carbenoids over the donor group. The ester group aligns perpendicular to the carbene plane, and blocks attack on its side. When the substrate approaches over the donor group, the aryl ring of the ligand blocks the *Re*-face, leaving the *Si*-face open for the attack. This model correctly predicts the observed absolute configuration of the products.

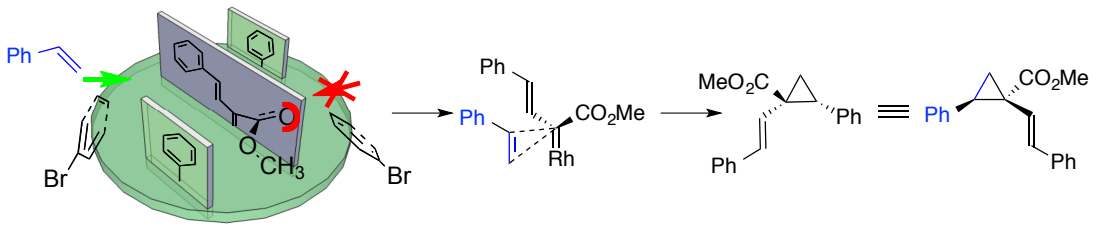


Figure 3.8 Model on Rh_2(*R*-BTPCP)$_4$-catalyzed transformation

3.3 Conclusion

In this chapter, we have developed a family of new dirhodium tetrakis(triarylcyclopropanecarboxylate) catalysts. These new catalysts can be synthesized in three steps in decent yields. The use of the well-established Rh_2(DOSP)$_4$ catalyzed cyclopropanation as enabling technology to access the chiral cyclopropane carboxylate ligands for new dirhodium catalysts design added a great value for carbene chemistry; also, with this cyclopropanation technology in hand, a diverse range of new dirhodium catalysts with different electronic and steric properties could be synthesized, which diversify the design of new dirhodium catalysts library and have the potential to discover new possibilities in carbene chemistry.

The utility of Rh_2(*R*-BTPCP)$_4$ has been demonstrated in a variety of highly enantioselective carbene transformations, particularly when dichloromethane was used as a solvent, which addressed the long-standing issue on hydrocarbon solvent-dependent enantioselectivity that was observed with Rh_2(*R*-DOSP)$_4$. Moreover, when the bigger size of esters was used as acceptor groups on diazoacetates, the asymmetric induction in standard cyclopropanation remained very high or was slightly improved, but the

corresponding enantioselectivity was dramatically eroded when Rh_2(*R*-DOSP)$_4$ was used in the same reaction.

The X-ray crystal study of the new catalyst indicated that Rh_2(*R*-BTPCP)$_4$ has a D_2-symmetric conformation and is sterically demanding. Also, a predictive model to rationalize the observed stereoselectivity in the cyclopropanation with Rh_2(*R*-BTPCP)$_4$ was proposed with the assistance of computational studies; interestingly, the study suggested that the two *para*-bromophenyl groups have to rotate in the same direction to make room for the carbene, which further illustrated the bulky feature of this catalyst.

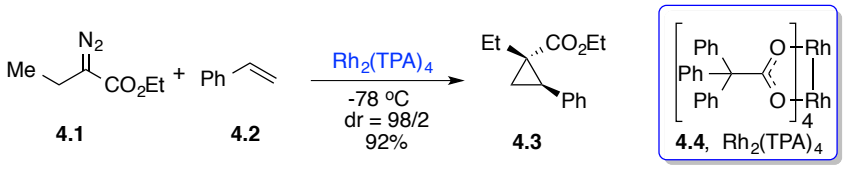
These studies help us better understand the unique structural features of these novel dirhodium cyclopropane carboxylate catalysts; with this knowledge and insights in mind, it set a strong foundation for a program directed towards the discovery of new carbene transformations that were impossible to achieve with other catalysts.

Chapter IV

Influence of Sterically Bulky Catalysts on Intramolecular Cyclopropanation: Enantioselective Synthesis of 2-Arylbicyclo[1.1.0]butane Carboxylates

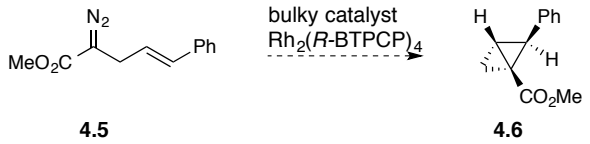
4.1 Introduction

The newly designed dirhodium triarylcyclopropane carboxylate catalysts are sterically demanding. Therefore, it became of interest to determine how this characteristic could be exploited in new types of rhodium carbenoid reactions. Recently, it was reported that the stericaly bulky triphenylacetate catalyst $Rh_2(TPA)_4$ (**4.4**) inhibited undesirable β-hydride shift of the carbene derived from alkyldiazoacetate[47] (**4.1**). Instead, an intermolecular cyclopropanation took place and afforded the cyclopropane (**4.3**) in 92% yield with high diastereoselectivity (Scheme 4.1).



Scheme 4.1 Inhibiting β-hydride shift from metallocarbene with bulky $Rh_2(TPA)_4$

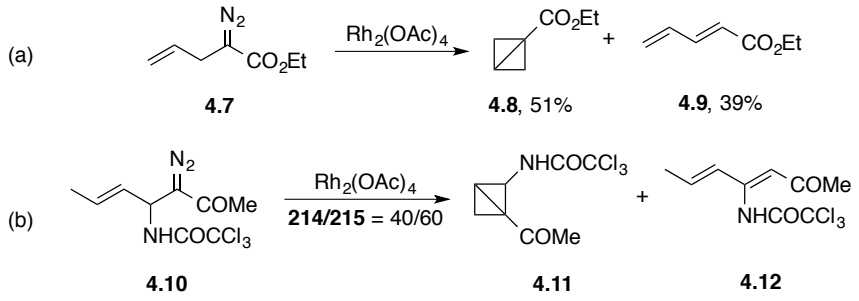
We considered that an intriguing opportunity to showcase the influence of bulky catalysts would be the intramolecular cyclopropanation of α-allyldiazoacetates (**4.5**) derivatives to form bicyclobutanes (**4.6**) (Scheme 4.2). The resulting carbenes would be prone to a β-hydride shift but hopefully the catalyst will influence which product is formed.



4.5 **4.6**

Scheme 4.2 Intramolecular cyclopropanation of α-allyldiazoacetates

Early studies indicated that rhodium acetate-catalyzed decomposition of α-allyl diazoacetates (**4.7**) gave the bicyclo[1.1.0]butane (**4.8**) in 51% yield with a formation of diene (**4.9**) in 39% yield (Scheme 4.3, a).[48] The use of diazoacetate (**4.10**) in the presence of catalytic amounts of rhodium acetate also resulted in a mixture of bicyclo[1.1.0]butane (**4.11**) and diene (**4.12**)[49] (Scheme 4.3, b). Thus, these precedence demonstrated the formation of bicyclo[1.1.0]butanes from α-allyl diazoacetates but the β-hydride shift was a competing process.



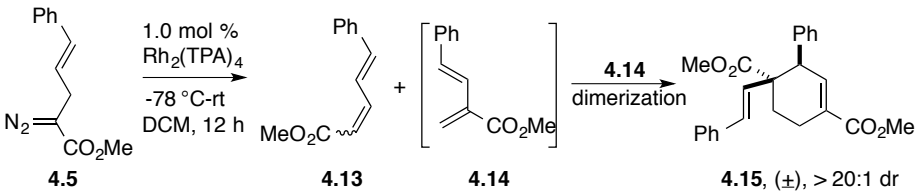
Scheme 4.3 Intramolecular cyclopropanation towards bicyclo[1.1.0]butane

4.2 Results and discussion

4.2.1 Discovery and optimization

Our initial study began with the rhodium-catalyzed decomposition of α-cinnamyldiazoacetate (**4.5**) with $Rh_2(TPA)_4$, an electron-rich and sterically crowded catalyst (Scheme 4.4). The $Rh_2(TPA)_4$-catalyzed decomposition of diazo (**4.5**) failed to provide the desired bicyclo[1.1.0]butane product. Instead, a mixture of diene (**4.13**) and cyclohexene product (**4.15**) was obtained. Cyclohexene (**4.15**), isolated in 69% yield, was

presumably formed by dimerization of the diene (**4.14**), which was produced *in situ* in the reaction. The cyclohexene product (**4.15**) was confirmed by X-ray crystallographic analysis (Figure 4.1).



Scheme 4.4 $Rh_2(TPA)_4$-catalyzed decomposition of α-cinnamyldiazoacetate

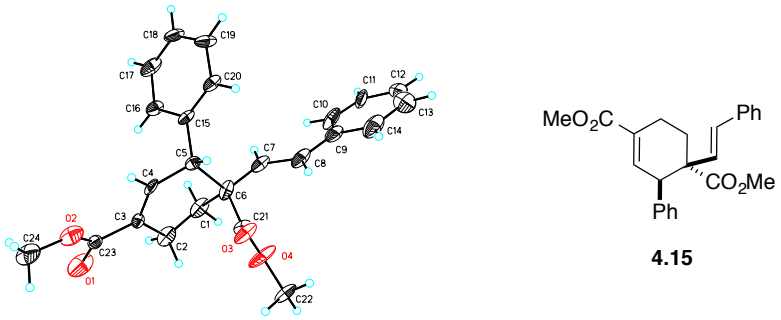
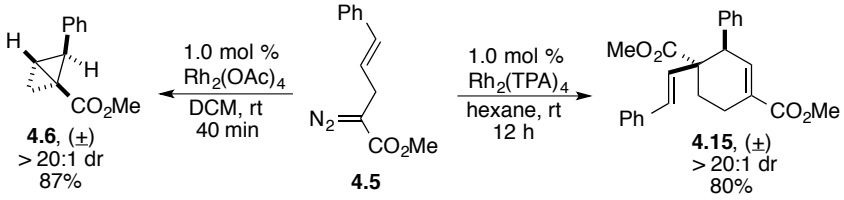


Figure 4.1 X-ray crystal structure of cyclohexene product



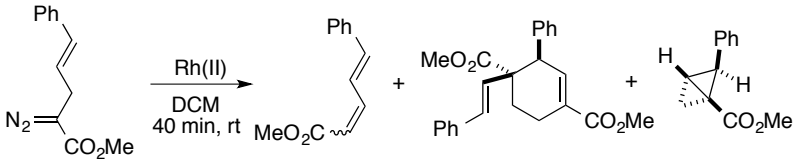
Scheme 4.5 Divergent synthesis of bicyclo[1.1.0]butane and cyclohexene

Further exploratory studies revealed that the product outcome was dependent on the reaction solvent, time and the catalyst (Scheme 4.5). When the reaction with $Rh_2(TPA)_4$ was conducted in hexane at room temperature for 12 h, cyclohexene (**4.15**) could be isolated in 80% yield; however, when $Rh_2(OAc)_4$ was used as catalyst in

dichloromethane, the desired 2-phenylbicyclo[1.1.0]butane carboxylate (**4.6**) was obtained in 87% yield.

As $Rh_2(OAc)_4$ is only partially soluble in dichloromethane, we reasoned that only a trace amount of catalyst may be required to decompose the diazo compound (**4.5**) and generate the bicyclobutane (**4.6**), but (**4.6**) may undergo a slower rhodium-catalyzed rearrangement to (**4.14**) and subsequent dimerization into product (**4.15**). On the basis of this hypothesis, we examined a series of catalysts at standard (1 mol%) and low catalyst loadings (0.01 mol%) (Table 4.1). The formation of bicyclo[1.1.0]butane (**4.6**) was favored at low catalyst loadings in all cases. Under conditions with 0.01 mol% of $Rh_2(OOct)_4$, (**4.6**) was formed in 85% isolated yield (Table 4.1, entry 4).

Table 4.1 Type of catalyst and catalyst loading evaluation



4.5 **4.13 (a)** **4.15 (b)** **4.6 (c)**

entry	catalyst	cat. loading (mol %)	yield ratio (**a/b/c**)[a]	yield (%)[b]
1	$Rh_2(OPiv)_4$	1.0	10/10/80	62
2	$Rh_2(OPiv)_4$	0.01	4/trace/96	80
3	$Rh_2(OOct)_4$	1.0	16/18/66	60
4	$Rh_2(OOct)_4$	0.01	2/trace/98	85
5	$Rh_2(TPA)_4$	1.0	25/64/11	10
6	$Rh_2(TPA)_4$	0.01	8/33/59	47

[a] Ratio was calculated from the NMR of the reaction mixture prior to chromatographic purification and takes into account that 2.0 equiv of (**4.5**) is required for the formation of (**4.15**). [b] Isolated yield of (**4.6**) (> 20:1 dr).

Having developed a practical entry into the bicyclo[1.1.0]butane system, we subsequently focused on achieving an asymmetric version of this process with a chiral dirhodium catalyst (Figure 4.2) at very low catalyst loading (0.01 mol%). The standard chiral dirhodium tetracarboxylate catalysts, Rh_2(*R*-DOSP)$_4$, Rh_2(*S*-PTAD)$_4$ and Rh_2(*S*-

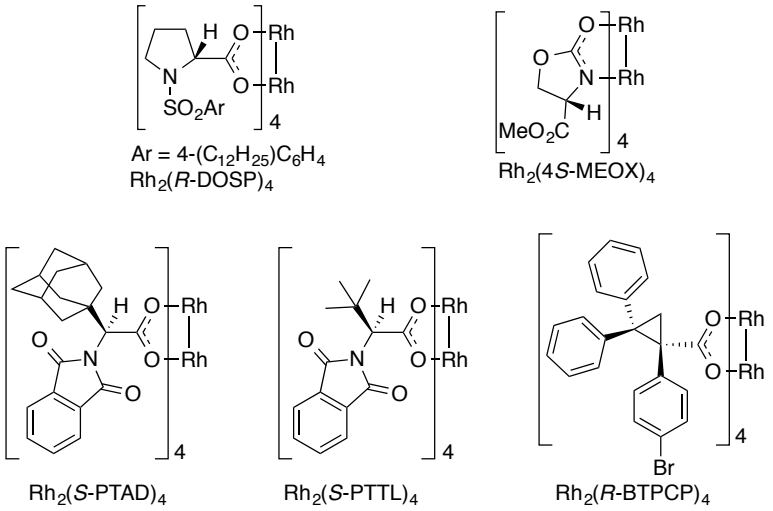
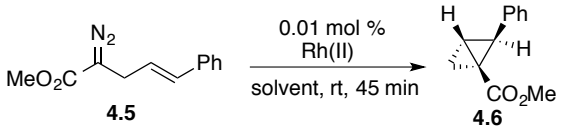


Figure 4.2 Chiral dirhodium catalysts in bicyclo[1.1.0]butane synthesis

Table 4.2 Chiral catalyst evaluations



4.5 **4.6**

entry	catalyst	solvent	yield(%)[a]	ee(%)[b]
1	Rh_2(*R*-DOSP)$_4$	DCM	65	<5
2	Rh_2(*S*-PTAD)$_4$	DCM	64	47
3	Rh_2(*S*-PTTL)$_4$	DCM	69	52
4[c]	Rh_2(4*S*-MEOX)$_4$	DCM	42	-23
5	Rh_2(*R*-BTPCP)$_4$	DCM	72	90
6	Rh_2(*R*-BTPCP)$_4$	hexane	64	88
7	Rh_2(*R*-BTPCP)$_4$	acetone	60	94
8	Rh_2(*R*-BTPCP)$_4$	EtOAc	70	94

[a] Isolated yield. [b] HPLC analysis, >20:1 dr. [c] 0.5 mol% catalyst loading.

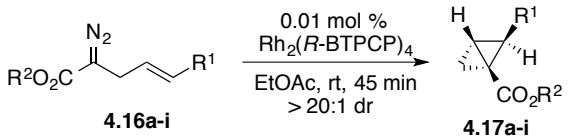
PTTL)$_4$ resulted in effective formation of (**4.6**), but the level of enantioinduction was relatively low in each case (Table 4.2, entries 1-3). Dirhodium tetracarboxamidate catalyst, Rh_2(4*S*-MEOX)$_4$, a less reactive catalyst, also resulted in the formation of (**4.6**) with a higher catalyst loading (0.5 mol%), but bicyclo[1.1.0]butane carboxylate (**4.6**) was still produced with low levels of enantioselectivity (Table 4.2, entry 4). The breakthrough catalyst for high asymmetric induction was the triarylcyclopropane carboxylate complex Rh_2(*R*-BTPCP)$_4$, which provided (**4.6**) in 72% yield and 90% ee in dichloromethane

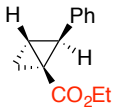
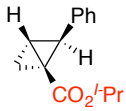
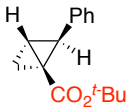
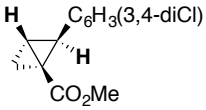
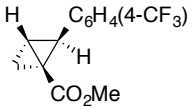
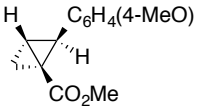
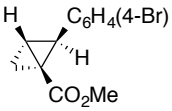
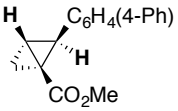
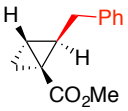
(Table 4.2, entry 5). Furthermore, when ethyl acetate was used as solvent, the asymmetric induction of this transformation can be improved to 94% ee (Table 4.2, entry 8).

4.2.2 Scope of bicyclo[1.1.0]butane and cyclohexene

Rh_2(*R*-BTPCP)$_4$ proved to be an effective catalyst for the asymmetric synthesis of a range of 2-arylbicyclo[1.1.0]butane carboxylates as summarized in Table 4.3.

Table 4.3 Scope of bicyclo[1.1.0]butane carboxylate



 **4.17a**, 74% 94% ee	 **4.17b**, 64% 93% ee	 **4.17c**, 45% 70% ee
 **4.17d**, 65% 90% ee	 **4.17e**, 63% 94% ee	 **4.17f**, 66% 85% ee
 **4.17g**, 66% 93% ee	 **4.17h**, 61% 91% ee	 **4.17i**, 74% 51% ee

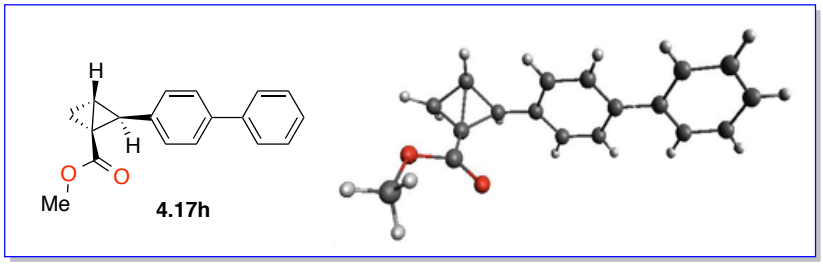
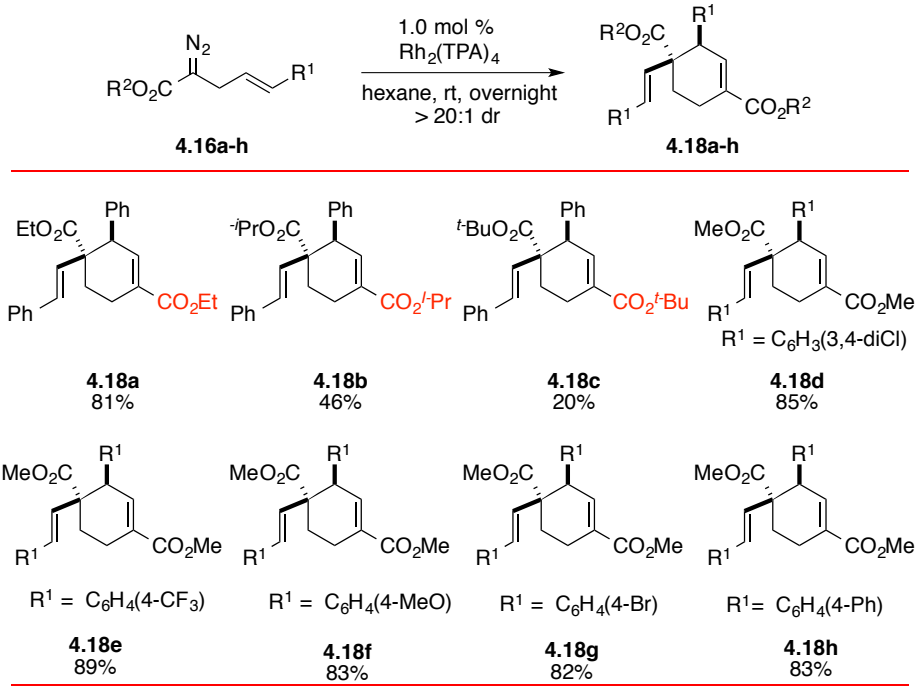


Figure 4.3 X-ray crystal structure of bicyclo[1.1.0]butane **4.17h**

Lower enantioselectivity was observed when the ester group was *tert*-butyl on diazoacetate, affording the product (**4.17c**) in 70% ee. When the aryl ring was electron rich such as *p*-methoxyphenyl, the product (**4.17f**) was obtained in 66% yield and 85% ee. The use of a benzyl group on the terminal alkene further eroded the asymmetric induction, providing the product (**4.17i**) in 51% ee. The other 2-arylbicyclo[1.1.0]butane carboxylates were formed in good yields (61%-74%) with high levels of enantioinduction (>90% ee). The absolute configuration of 2-aryl bicyclo[1.1.0]butane carboxylate (**4.17h**) was confirmed by X-ray crystallography (Figure 4.3). The configurations of the other bicylco[1.1.0]butane products are tentatively assigned by analogy.

Even though bicyclo[1.1.0[butanes could be isolated in high yield, these products could be totally eliminated when 1.0 mol% of $Rh_2(TPA)_4$ and extended reaction times were used. Under these conditions, cyclohexenes were obtained in good yields (81-89%) for a variety of methyl cinnamyldiazoacetates (Table 4.4).

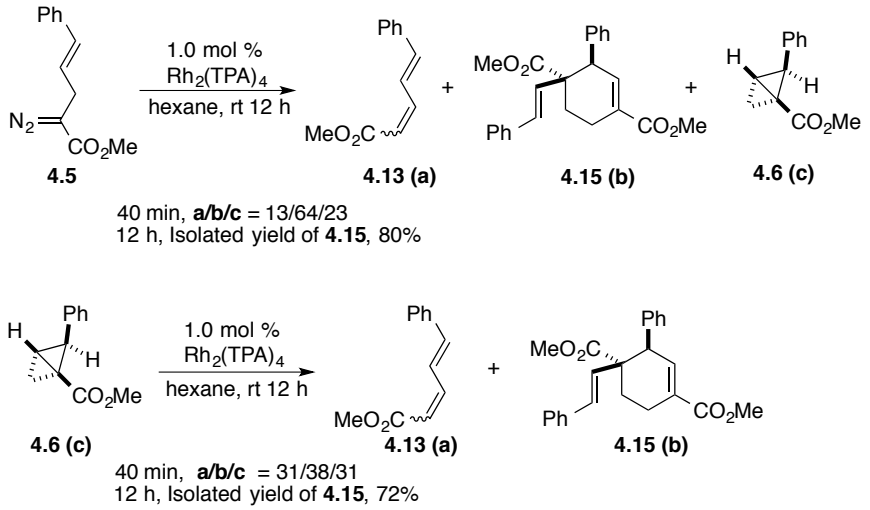
Table 4.4 Scope of cyclohexene



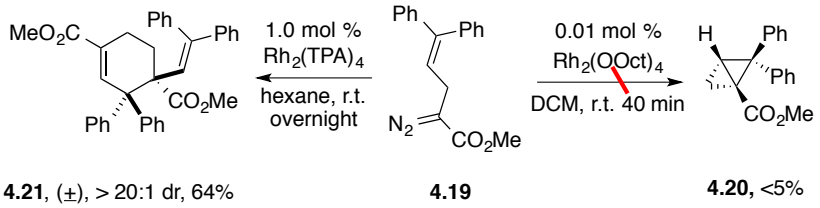
The bulky ester had bad influence for the formation of cyclohexene derivatives. For example, increasing the size of the ester to ethyl, *iso*-propyl and *tert*-butyl caused a steady drop in the isolated yield of cyclohexenes (**4.18a-c**). The electronic effects of the aryl group at the terminal alkene did not have great effects on the yield; for example, the product (**4.18e**) and (**4.18f**) were obtained in 89% and 83% isolated yield, respectively.

4.2.3 Mechanistic insights of cyclohexene formation

In order to probe the cause of the change in product distribution, further control experiments were conducted as illustrated in Scheme 4.6. The $Rh_2(TPA)_4$-catalyzed reaction of (**4.5**) was re-examined under short (40 min) and long (12 h) reaction times. After 40 min a mixture of the three products is present, but no 2-phenyl bicyclo[1.1.0]butane carboxylate (**4.6**) is present in the reaction mixture after 12 h. Under these conditions, cyclohexene (**4.15**) is isolated in 80% yield. Product (**4.6**) is stable in solution in the absence of catalyst for several days. However, when it was exposed to $Rh_2(TPA)_4$, within 40 min, over half of the material rearranges to diene (**4.13**) and the cycloadduct. After 12 h, none of (**4.6**) remains and (**4.15**) was isolated in 72% yield.



Scheme 4.6 Cyclohexene formation from rearrangement of bicyclo[1.1.0]butane

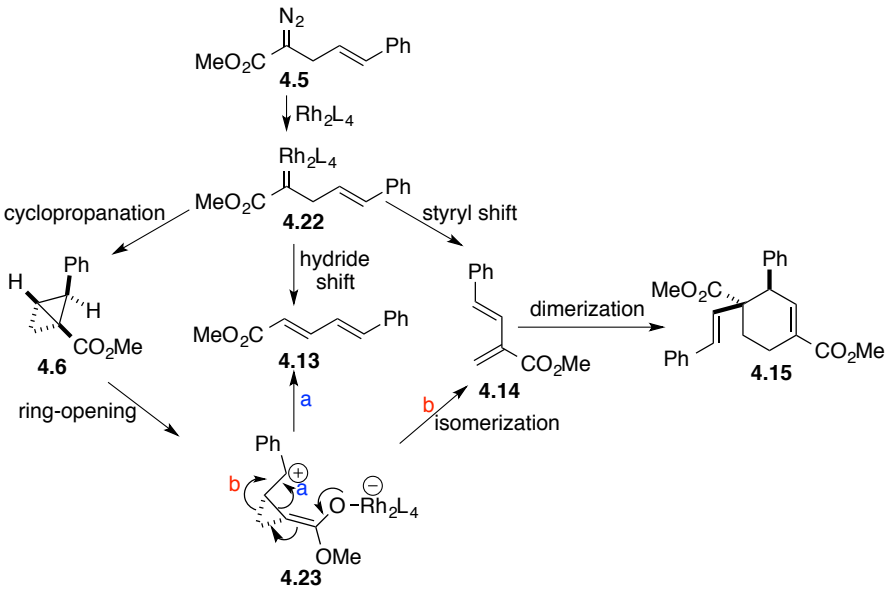


Scheme 4.7 Cyclohexene formation from direct vinyl shift/dimerization process

These experiments show that $Rh_2(TPA)_4$ catalyzes the ring opening of (**4.6**). However, as the ratio of (**4.15**) formed after 40 min is higher when starting from the diazo compound **(4.5**) than when starting from (**4.6**), it appears that at least some of the product (**4.15**) is formed directly from the carbenoid derived from (**4.6**). Further possible evidence to support the proposed direct vinyl shift might come from the rhodium-catalyzed decomposition of diazo (**4.19**), which afforded the cyclohexene product (**4.21**) in 64% yield but no detectable bicyclo[1.1.0]butane (**4.20**) was observed from ^{1}H NMR analysis (Scheme 4.11). This reaction might suggest the product (**4.21**) comes form direct vinyl shift/dimerization process.

A reasonable series of mechanisms for these transformations is shown in Scheme 4.12. 1,2-hydride shift from alkyl rhodium carbene species has been well documented.[50] In the reaction, dienes (**4.13**) and (**4.14**) can be generated directly from the allyl carbenoid (**4.22**) *via* a 1,2-shift of either a hydride or a styryl group. Direct cyclopropanation of allyl carbenoid (**4.22** would generate the bicyclo[1.1.0]butane (**4.6**). Previously, the metal-catalyzed isomerization of bicyclo[1.1.0]butane system into 1,4-butadiene has also been well-documented.[51] Based on the experimental observations in this reaction, the bicyclo[1.1.0]butane carboxylate is also unstable in the presence of the dirhodium catalysts, undergoing ring-opening to intermediate (**4.23**) and then bond breaking to form either (**4.13**) (bond a) or (**4.14**) (bond b). The rhodium catalyzed ring opening of (**4.6**) is

slower than the rhodium-catalyzed nitrogen extrusion to form the carbenoid intermediates. Therefore, when very low catalyst loading and relatively short reaction times are used, the bicyclo[1.1.0]butane (**4.6**) can be selectively isolated.



Scheme 4.8 Proposed possible mechanism for cyclohexene formation

4.3 Conclusion

In this chapter, we discussed our results on asymmetric synthesis of bicyclo[1.1.0]butane carboxylates through a dirhodium-catalyzed intramolecular cyclopropanation strategy. The use of sterically crowded chiral dirhodium triarylcyclopropane carboxylate was originally expected to inhibit the facile β-hydride elimination in allyldiazoacetates and promote the intramolecular cyclopropanation event, but the study demonstrated that the choice of catalysts and catalyst loadings are of great importance to the outcome of product, providing either 2-arylbicyclo[1.1.0]butane carboxylates or cyclohexene derivatives. Particularly, both products are produced in a highly diastereoselective manner, with 2-arylbicyclo[1.1.0]butane carboxylates preferentially formed under low catalyst loadings. Control experiment also suggested that

the bicyclo[1.1.0]butane carboxylates formed in the reaction could undergo a rearrangement to generate cyclohexene products under dirhodium carboxylate catalysts when the reaction time was kept longer. An asymmetric study with optimization of different chiral dirhodium catalysts was also conducted. The use of the new designed dirhodium triarylcyclopropane carboxylate Rh_2(*R*-BTPCP)$_4$ was the key to achieve high enantioselectivity.

Chapter V
Influence of Sterically Crowded Dirhodium Catalysts on the Vinylogous Transformations of Metallovinylcarbenes

5.1 Introduction

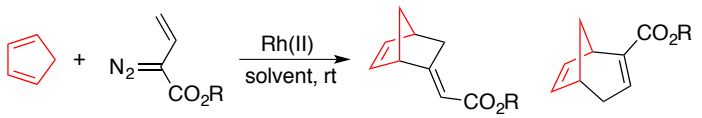
Metallovinylcarbenes are attractive intermediates in organic synthesis.[28] In addition to the normal carbenoid reactivity, they are also capable of undergoing reactions that are initiated by nucleophilic attack at the vinylogous position of the carbenoid. Recently, a discovery was made in the Davies group that indicated that a bulky catalyst would be able to enhance reactions at the vinylogous site rather than the carbenoid site.[52] This introduction will describe the early work on vinylogous reactivity of rhodium vinylcarbenes. This will be followed by a description of the recent advances that showed that the conformation of the rhodium vinylcarbenes is influenced by the nature of the catalyst, which lead to enhanced vinylogous reactivity.

5.1.1 Seminal work on vinylogous reactivity

Over 20 years ago, the Davies group did some systematic investigations and found that through judicious choice of substrates and reaction conditions, it was possible to control the site selectivity of the metallovinylcarbene transformations. In 1990, Davies and co-workers first discovered that γ-unsubstituted vinylcarbenoids were particularly prone to exhibit electrophilic reactivity at the terminal site.[53] Rh(II)-carboxylate catalyzed reaction between cyclopentadiene (**5.1**) and vinyldiazoacetates (**5.2a**) in pentane gave a formal

[4+3]-cycloaddition product (**5.4a**) (Table 5.1, entry 1), but resulted in a mixture of (**5.3a**) and (**5.4a**) in benzene (Table 5.1, entry 2). A slight shift towards the formation of product (**5.3a**) was observed when a polar dichloromethane solvent was used (Table 5.1, entry 3). Further study suggests that the distribution of these products was dependent on the nature of the catalyst and the solvent. A more polar solvent and electron deficient catalyst favored reaction at the vinylogous position. A third factor is that typical carbenoid reactivity in vinylcarbenoids could be disrupted when a bulky ester adjacent to the carbene is used.[54] The use of *tert*-butyl ester did not improve the selectivity, but the outcome of the reaction was dramatically changed when the bulky BHT-ester was used, which gave exclusive (**5.3c**) (Table 5.1, entry 6). The discovery on tolerance of enantioselectivity when bulky ester was used in the Chapter III and the use of bulky ester enhanced vinylogous reactivity are important guidelines to choose substrates for my project on bulky dirhodium-catalyzed vinylogous transformations.

Table 5.1 Early studies of vinylogous transformations of rhodiumvinylcarbenes



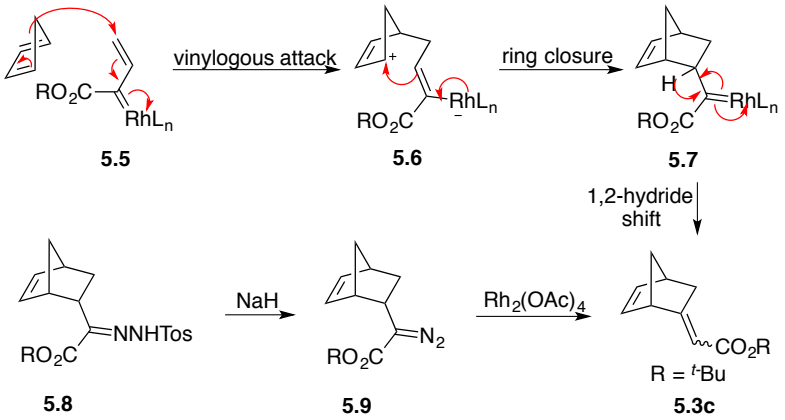
5.1 **5.2a-c** **5.3a-c** **5.4a-c**

entry	diazo	catalyst	solvent	R	**5.3**:**5.4** (ratio)
1	a	$Rh_2(OAc)_4$	pentane	Me	5:95
2	a	$Rh_2(OAc)_4$	benzene	Me	16:84
3	a	$Rh_2(OAc)_4$	DCM	Me	33/67
4	a	$Rh_2(TFA)_4$	DCM	Me	68:32
5	b	$Rh_2(OAc)_4$	DCM	^{t}Bu	48:52
6	c	$Rh_2(OAc)_4$	DCM	**BHT[a]**	**100:0**

[a]BHT refers to 2,6-di(^{t}Bu)-4-MePh

The rationale for the formation of unusual product (**5.3c**) was listed in Scheme 5.1. The reaction was proposed to occur through a *s-trans* configuration, and upon vinylogous

attack, it formed a rhodiumvinyl species (**5.6**) that cannot close to form a seven membered ring; instead, the [4+2]-ring closure to form a second metallocarbene species[53] (**5.7**). A [1,2]-shift would generate the product (**5.3c**). Also, a control experiment indicated that the proposed second carbenoid (**5.7**) is a viable intermediate as the rhodium-catalyzed decomposition of corresponding diazoacetate, illustrated by *tert*-butyl ester diazoacetate (**5.9**), under same reaction conditions, also gave the product (**5.3c**). Furthermore, the dependence of the *E*/*Z* isomeric ratio of (**5.3c**) on catalyst structure supports the existence of the second carbenoid intermediate. This early observation provided an experimental evidence and support for the recent discovery on a formal [3+2]-annulation that will be discussed in this Chapter later.

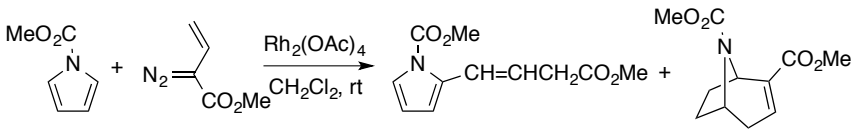


Scheme 5.1 The rationale for product **5.3c** formation

Another example of vinylogous reactivity was observed in the dirhodium-catalyzed reaction between *N*-carbomethoxypyrrole and vinyldiazoacetate in 1991[55] (Table 5.2). The use of $Rh_2(OAc)_4$ in the reaction with dichloromethane as solvent did not show preference for vinylogous reactivity, affording a 45:55 mixture of product (**5.11**) and (**5.12**) (Table 5.2, entry 1). The electron-deficient $Rh_2(TFA)_4$ catalyst enhanced the

vinylogous reactivity in dichloromethane, but the selectivity was dropped when the nonpolar solvent was used in the reaction (Table 5.2, entry 3).

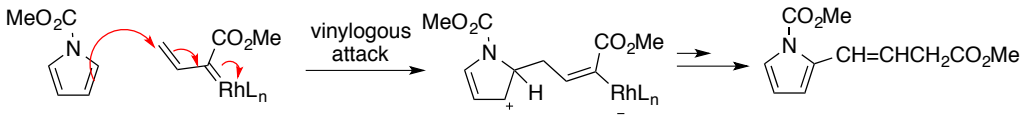
Table 5.2 Early studies of vinylogous reactivity with *N*-carbomethoxypyrrole



5.10 **5.2a** **5.11 (I)** **5.12 (II)**

entry	catalyst	solvent	**I:II** (ratio)
1	$Rh_2(OAc)_4$	DCM	45:55
2	$Rh_2(TFA)_4$	DCM	85:15
3	$Rh_2(TFA)_4$	hexane	74:26

The mechanism for product (**5.11**) formation was listed (Scheme 5.3). It was proposed to start with vinylogous addition to form a zwitterionic intermediate (**5.14**). There are two possible pathways for conversion of (**5.14**) to (**5.11**). One possibility would be the generation of a new carbenoid species by rearomatization of the pyrrole and protonation of the vinylrhodium, which could then undergo a [1,2]-hydride shift followed by isomerization of the newly formed double bond into conjugation with the aromatic ring to form (**5.11**). Alternatively, rearomatization of (**5.14**) could be facilitated intramolecularly to generate a rhodium hydride species, which would then undergo reductive elimination and double bond isomerization to generate (**5.11**). The involvement of rhodium hydride species has been proposed in carbenoid C-H insertions and this intermediate is an intriguing possibility because some dissociation of the carboxylate ligands would be required.

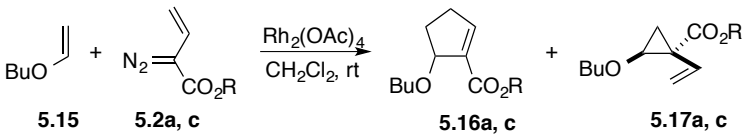


5.10 **5.13** **5.14** **5.11**

Scheme 5.2 Proposed mechanism for reaction of *N*-carbomethoxypyrrole

The influence of a bulky ester on enhancing vinylogous reactivity was also observed in the early study between vinyldiazoacetates and butyl vinyl ether[56] (Table 5.3). The use of TBH ester on diazoacetate (**5.2c**) inhibited the cyclopropanation and afforded the formal [3+2]-annulation product (**5.16c**) in 90% isolated yield. The cyclopropane product (**5.17**) could undergo a vinylcyclopropane/cyclopentene rearrangement, but the expected cyclopentene from such a rearrangement would be a regio-isomer of product (**5.16**). Also, the product (**5.17**) was stable under the reaction conditions and thus ruled out the possible isomerization pathway.

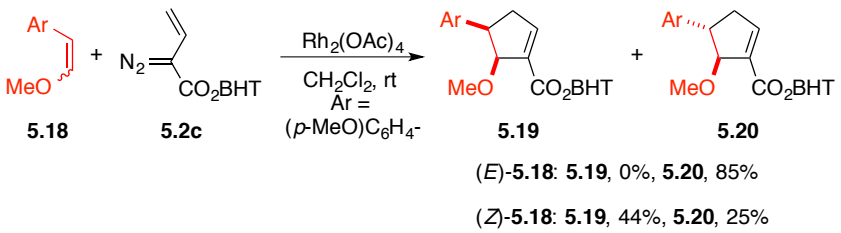
Table 5.3 Vinylogous reactivity in a reaction with butyl vinyl ether



5.15 **5.2a, c** **5.16a, c** **5.17a, c**

entry	diazo	**5.16**-yield(%)	**5.17**-yield(%)
1	**5.2a**	24	37
2	**5.2c**	90	0

To gain information on the reaction mechanism, the question of stereocontrol was examined by decomposition of the vinyldiazoacetate (**5.2c**) in the presence of either *E* or *Z* vinyl ether (**5.18**). The reaction with *E* vinyl ether gave exclusive *trans*-cyclopentene cycloadduct (**5.20**) while the *Z* vinyl ether resulted in a mixture of *cis*- and *trans*-cyclopentene, which indicated the formation of zwitterionic intermediate would be highly possible. Furthermore, the formation of a formal [3+2]-annulation derivative indicated that the reaction was likely to proceed through a *s-cis* conformation of rhodium vinylcarbene because the reaction undergoing with a *s-trans* conformation of rhodium vinylcarbene would be hard to close the cyclopentene ring.



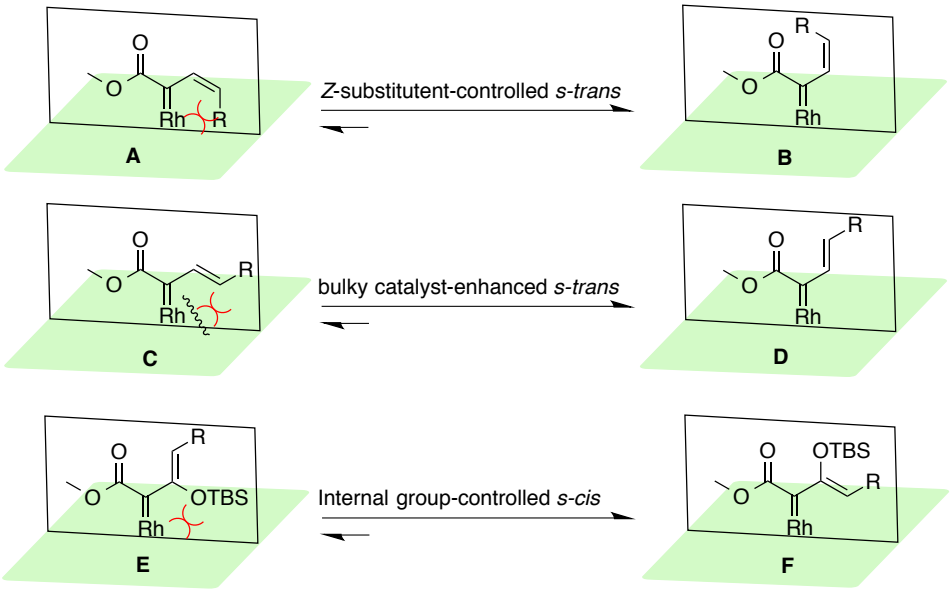
Scheme 5.3 Stereochemical outcome in vinylogous transformation

From these early studies on vinylogous transformations, it was found that enhancement of vinylogous reactivity can be harvested by using electron-poor ligand on dirhodium catalysts, a polar solvent and a bulky ester on diazoacetates. Importantly, the recent observation on important relationship between the conformation and reactivity of rhodium vinylcarbenes is very important because it opened up a new door to enhance the vinylogous reactivity by catalyst design.

5.1.2 Recent results on vinylcabenoid reactions

An important factor discovered recently was that vinylogous reactivity is dependent on the conformation of the vinylcarbenoid intermediates, in which the *s-trans* conformation of vinylcarbenoids generally favors vinylogous reactivity compared to the carbenoid in the *s-cis* conformation.[57] Importantly, this allowed for the possibility of achieving vinylogous reactivity with vinylcarbenes substituted at the vinyl terminus. The factors that control the conformations of rhodium vinylcarbenes are summarized in Scheme 5.4. A *Z*-substituent on the vinylcarbene interferes with the catalyst wall in the *s-cis* conformation **A** and so the rhodium carbene would preferentially exist in the *s-trans* conformation **B**. A highly bulky chiral dirhodium catalyst interferes with the *E*-alkene in conformation **C** and therefore the rhodium carbene would preferentially exist in the *s-trans* conformation **D**. The catalyst wall interferes with the internal substituent on

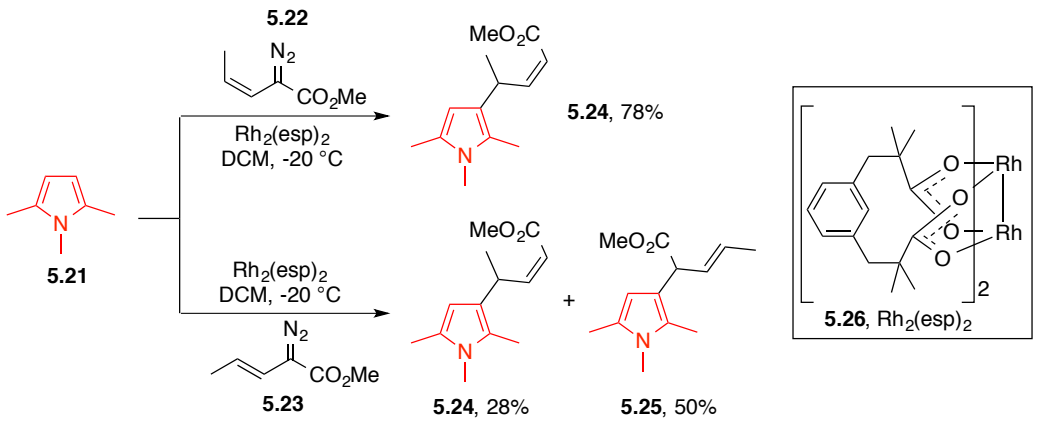
vinylcarbene conformation **E** and accordingly the *s-cis* conformation of vinylcarbene **F** would be favored.



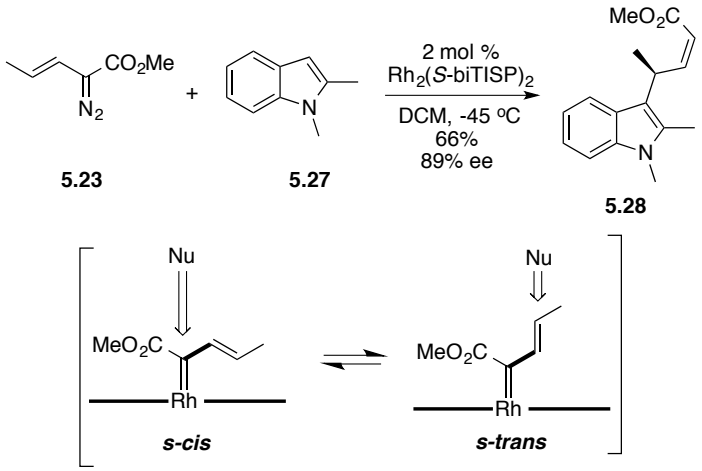
Scheme 5.4 General Influence on the conformations of rhodium vinylcarbenes

One recent example in the Davies group is a good case in point to illustrate the *s-trans* configuration-enhanced vinylogous reactivity compared to the *s-cis* configuration.[57] It was found that decomposition of *Z*-vinyldiazoacetate (**5.22**) with $Rh_2(esp)_2$ (**5.26**) as catalyst could undergo selective vinylogous alkylation with sterically hindered pyrroles (**5.21**); while *E*-vinyldiazoacetate (**5.23**) gave a mixture of vinylogous (**5.24**) and carbenoid alkylation (**5.25**) products (Scheme 5.5).

Scheme 5.6 illustrates an application of this phenomenon for the enantioselective functionalization of indoles.[52] In this reaction, the carbon-carbon bond formation took place at the vinylogous position of vinylrhoidium carbene instead of the carbenic site when the steircally bulky Rh_2(*S*-bi-TISP)$_2$ was used. The product (**5.28**) was obtained in 66% yield and 89% ee. The reason why the vinylogous reactivity is favored in this case is



Scheme 5.5 The discovery of *Z*-vinyldiazoacetate enhanced vinylogous reactivity

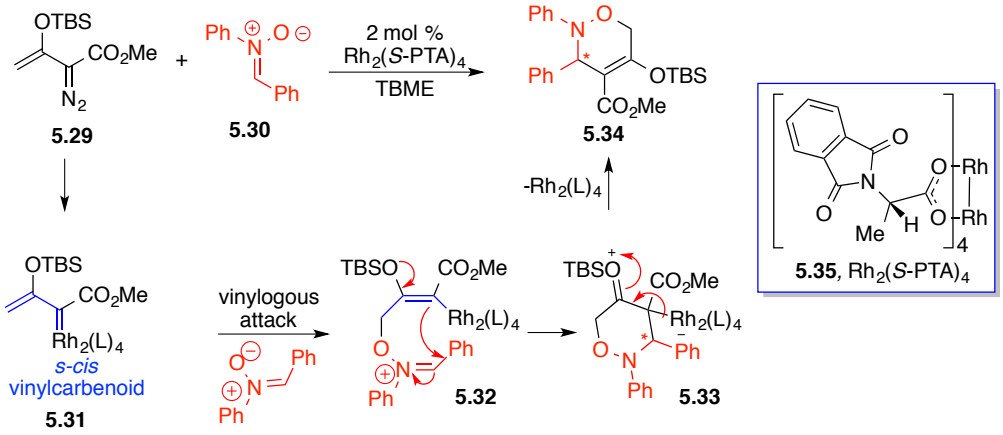


Scheme 5.6 Vinylogous reactivity of rhodium carbenoids

that the carbenoid was pushed to the *s-trans* conformation by the bulky catalyst, in which the carbenic site was blocked by the bulkiness of the catalyst, and the vinylogous site became more exposable to be attacked by nucleophile.[52] In this situation, the *cis* olefin configuration of product (**5.28**) would be generated upon attack followed by protonation of the vinyl rhodium with retention of configuration.

A study by Doyle and co-workers is particularly relevant to the work described in this thesis[58] (Scheme 5.7). A rhodium-catalyzed reaction of nitrones (**5.30**) with β-silyloxyvinyldiazoacetate (**5.29**) afforded [3+3] cycloadducts. Doyle proposed a

mechanism involving a *s-cis* carbenoid (**5.31**), which undergoes vinylogous attack by the nitrone, a vinyl rhodium, which also contains a vinyl ether (**5.32**) was formed. Doyle suggests that the vinyl ether then attacks the iminium to close the ring followed by elimination of rhodium catalyst to generate the product[58] (**5.34**). However, an alternative mechanism would be the vinylrhodium acting as the nucleophile to directly form the final product (**5.34**). The major consequence of this alternative interpretation is the reacting configuration of the vinylcarbene determines whether the vinylrhodium has the correct geometry for direct ring closure. Changing the reacting configuration of the vinylcarbene led to the discovery of a [3+2]-annulation of *s-trans* vinylcarbene and nitrone by use of sterically demanding chiral dirhodium catalysts.



Scheme 5.7 Doyle's formal [3+2]-annulation of nitrones and vinyldiazoacetates

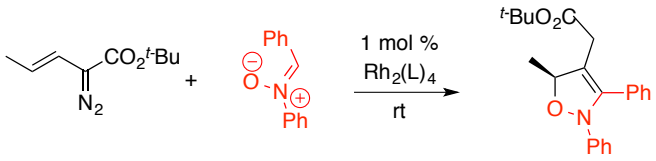
The studies on the triarylcyclopropane carboxylate catalysts described in Chapter III revealed that they were sterically demanding chiral catalysts. Therefore, we became intrigued with the application of this type of catalysts to enhance the *s-trans* configuration of rhodium vinylcarbene to explore the possibility of achieving an asymmetric [3+2]-annulation reaction with nitrones.

5.2 Formal [3+2]-annulation of nitrones with vinylcarbenes

5.2.1 Discovery and optimization

At the onset of this project, a bulky ester and bulky catalyst would be expected to enhance the vinylogous reactivity. Therefore, the effect of different dirhodium catalysts was examined on the reaction of (*E*)-*tert*-butyl 2-diazo-5-phenylpent-4-enoate (**5.36**) and nitrone (**5.30**). The results are summarized in Table 5.4.

Table 5.4 Initial optimization of formal [3+2]-annulation



5.36 **5.30** **5.37**

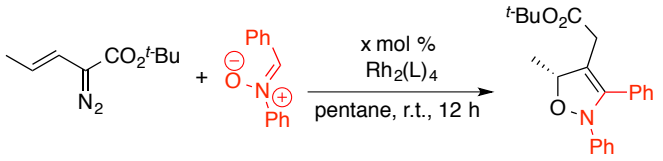
entry	catalyst	solvent	yield (%)[a]	ee (%)
1	Rh_2(*S*-DOSP)$_4$	pentane	<5	-
2	Rh_2(*S*-PTAD)$_4$	pentane	<5	-
3	Rh_2(*S*-PTTL)$_4$	pentane	<5	-
4	Rh_2(OOct)$_4$	pentane	<5	-
5	Rh_2(*S*-biTISP)$_2$	pentane	36	82
6	**Rh_2(*S*-BTPCP)$_4$**	**pentane**	**64**	**94**
7	Rh_2(*S*-BTPCP)$_4$	DCM	61	92
8	Rh_2(*S*-BTPCP)$_4$	acetone	30	95
9	Rh_2(*S*-BTPCP)$_4$	hexane	61	94

[a] Isolated yield, <5% means (**5.37**) was not observed from ^{1}H NMR analysis of the crude mixture prior to flash chromatography.

When sterically less crowded Rh_2(Oct)$_4$, Rh_2(*S*-DOSP)$_4$, Rh_2(*S*-PTAD)$_4$ and Rh_2(*S*-PTTL)$_4$ were used as catalysts, diazo compound (**5.36**) was not fully decomposed and the nitrone starting material was recovered. In contrast, the sterically bulky catalyst Rh_2(*S*-biTISP)$_2$ afforded the formal [3+2]-cycloadduct (**5.37**) in 32% yield and 82% ee (Table 5.4, entry 5). The yield and enantioselectivity was further improved using a more sterically congested catalyst Rh_2(*S*-BTPCP)$_4$ (Table 5.4, entry 6). Further optimization studies indicated pentane was the optimal solvent to conduct the reaction.

Considering the dramatic difference in outcome of the Rh_2(*S*-BTPCP)$_4$-catalyzed reactions compared to the reactions of the other dirhodium catalysts, a series of triarylcyclopropane carboxylate catalysts was evaluated (Table 5.5). All of these catalysts provided the desired product with high levels of enantioselectivity (94-98% ee). Increasing the size of the aryl group either in the *gem*- or *cis*- position to the carboxylate did not enhance the enantioselectivity. The unsubstituted triphenylcyclopropane carboxylate catalyst Rh_2(*R*-TPCP)$_4$ gave (*R*)-**5.17** with the highest level of enantioselectivity (98% ee, Table 5.5, entry 4). The isolated yield was further improved when the catalyst loading was 2 mol% (Table 5.5, entry 5). These studies once again underscore the importance of bulky dirhodium catalysts in vinylogous transformations of rhodium vinylcarbenes.

Table 5.5 Evaluation of dirhodium cyclopropane carboxylate catalysts



5.36 **5.30** ***(R)*-5.37**

entry	catalyst	x	yield (%)	ee (%)
1	Rh_2(*R*-NPCP)$_4$	1	59	94
2	Rh_2(*R*-BPCP)$_4$	1	58	94
3[a]	Rh_2(*S*-BNPCP)$_4$	1	52	94
4	Rh_2(*R*-TPCP)$_4$	1	67	98
5	**Rh_2(*R*-TPCP)$_4$**	**2**	**77**	**98**

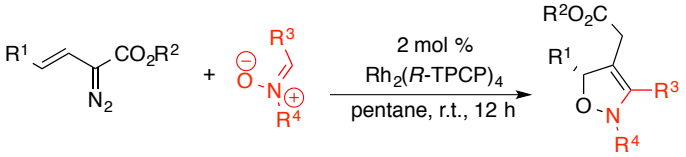
[a] Product has the opposite stereochemistry to that shown.

5.2.2 Substrate scope in formal [3+2]-annulation

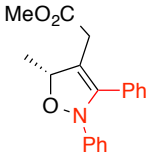
Having developed the optimized conditions, the scope of the formal [3+2]-cycloaddition was examined (Table 5.6). The size of ester group did not have a significant impact on the level of enantioselectivity but the yield was dropped when the smaller size of ester was used. For example, the methyl ester-derived product (**5.38a**) was

obtained in 47% isolated yield and 96% ee. Modification of the length of a linear alkyl chain at the vinyl terminus of the vinyldiazoacetate had little effect on the asymmetric induction, for example, the ethyl and n-butyl-derived products were obtained in the same

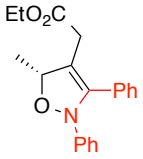
Table 5.6 Scope of formal [3+2]-annulation of nitrones and vinylcarbenes



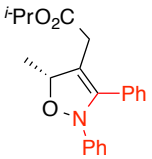
5.23, 5.36,**5.36a-e** **5.30**,**5.30a-i** **5.38a-o**



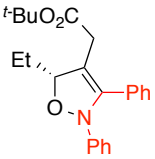
5.38a
47%
96% ee



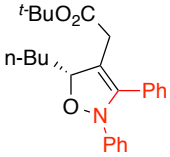
5.38b
58%
98% ee



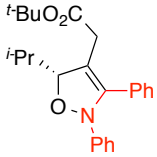
5.38c
67%
99% ee



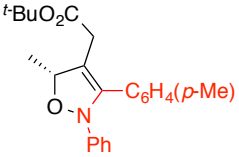
5.38d
72%
94% ee



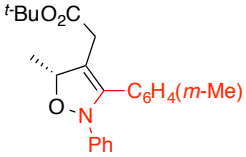
5.38e
62%
94% ee



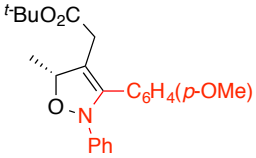
5.38f
51%
66% ee



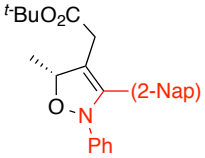
5.38g
70%
93% ee



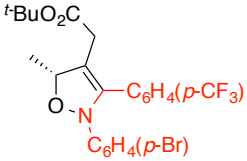
5.38h
64%
97% ee



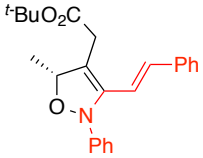
5.38i
60%
95% ee



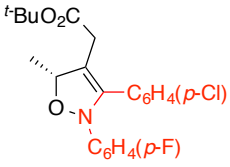
5.38j
69%
96% ee



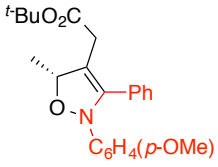
5.38k
42%
85% ee



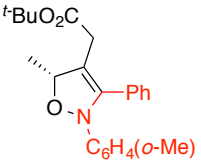
5.38l
62%
42% ee



5.38m
59%
95% ee



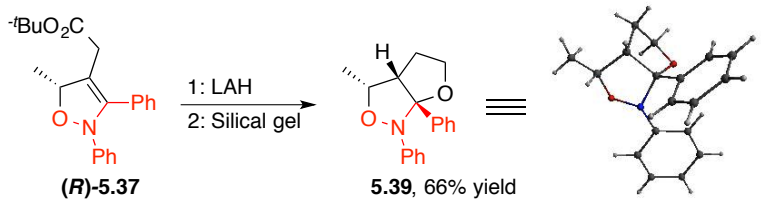
5.38n
66%
90% ee



5.38o
45%
87% ee

enantioselectivity (**5.38d-e**, both 94% ee), but a branched alkyl substituent such as an *iso*-propyl group, eroded the enantioselectivity (**5.38f**, 66% ee). The reaction can be conducted with a variety of nitrones, as illustrated by the range of products **5.38g-o** formed. The level of asymmetric induction was high for the aryl nitrones (85-97% ee) but much lower for the cinnamyl nitrone (**5.38l**, 42% ee).

To confirm the absolute configuration of the products, (***R*)-5.37** was transformed to the bicyclic product (**5.39**) in 66% yield (dr = 1.5/1) (Scheme 5.8), which was confirmed by X-ray single crystal analysis. The configurations of the other 2,5-dihydroisoxazole products are tentatively assigned by analogy.

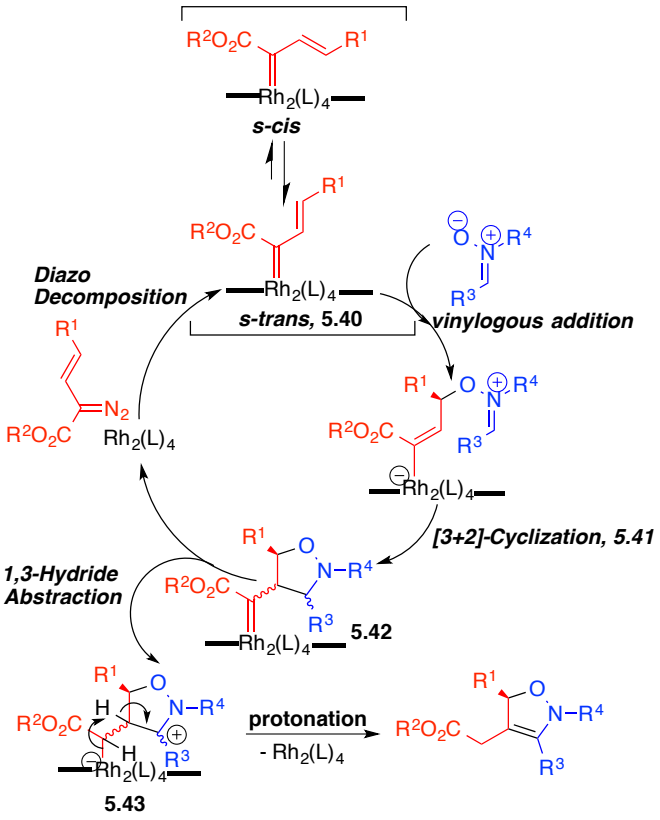


Scheme 5.8 Derivatization *via* reduction/cyclization process

5.2.3 Proposed mechanism of formal [3+2]-annulation

A catalytic cycle is proposed to rationalize the mechanism of the formal [3+2] cycloaddition (Scheme 5.9). It begins with rhodium-catalyzed decomposition of substituted vinyldiazoacetate. The bulky chiral rhodium catalyst provides a preferred *s-trans* carbenoid (**5.40**). Vinylogous attack by the nitrone affords a stable *cis*-rhodium-bonded vinyl species (**5.41**). At this stage, unlike the Doyle's reaction, ring-closure at the rhodium-bounded carbon in the [3+3]-approach became geometrically disfavored; instead, the ring-closure with viny lrhodium in the [3+2]-approach stands in the right geometry, which generates a new rhodium carbene species (**5.42**) upon cyclization. The new rhodium carbene (**5.42**) readily undergoes a 1,3-hydride abstraction to form the

zwitterion (**5.43**) followed by a proton transfer to afford the product. An alternative possibility would be 1,2-hydride migration followed by alkene isomerization. Another alternative mechanism that the second carbenoid intermediate (**5.42**) is formed by a concerted cycloaddition reaction between the nitrone and *s-trans*-(*E*)-methyl vinylcarbenoid intermediate is considered to be unlikely because of the well-known highly reactive rhodium carbenoid intermediates, though such mechanisms do occur with the more stable Fisher carbene complexes.[59]

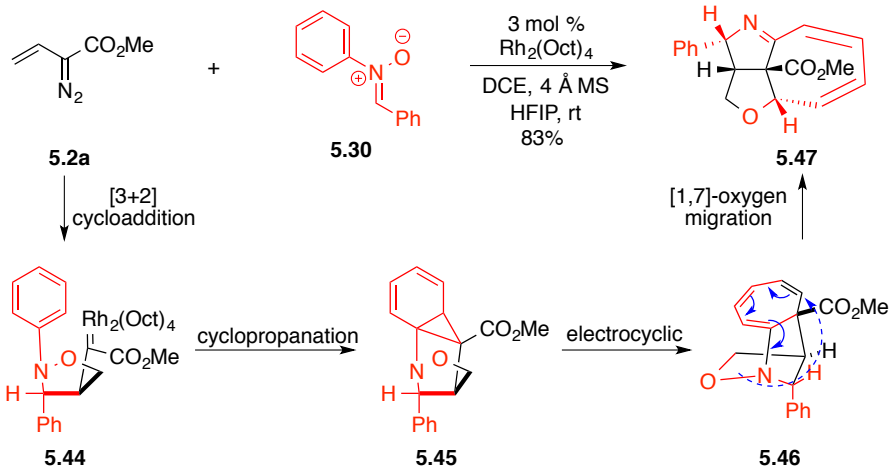


Scheme 5.9 Proposed catalytic cycle for formal [3+2]-annulation

5.2.4 Discovery of an intriguing cascade sequence

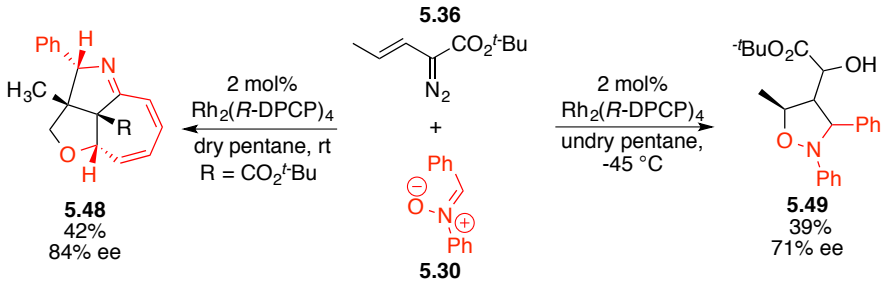
In the course of this study on vinylogous transformation with nitrone, an interesting paper published from the Doyle group deserved particular mention[60] (Scheme 5.10). When non-substituted vinyldiazoacetate (**5.2a**) was used, Doyle and co-workers reported

a cascade reaction. It was proposed to start with cycloaddition between rhodium vinylcarbene and nitrone to afford product (**5.44**), which underwent an aromatic cycloaddition/N-O cleavage and rearrangement, providing the tricyclic product (**5.47**) in highly region- and diastereoselective fashion. The authors speculated that the dirhodium carbene intermediate activates the adjacent vinyl group, which underwent a concerted [3+2]-cycloaddition with nitrone. From the studies described in this chapter, it is more likely that the reaction proceeds by a stepwise vinylogous addition followed by quick ring closure as described in this chapter .



Scheme 5.10 The Doyle's cascade reaction with nitrone

During this study, a similar cascade reaction was also observed when a sterically less hindered dirhodium diarylcyclopropane carboxylate catalyst was used in the reaction (Scheme 5.11). In the presence of dry pentane, the Rh_2(*R*-DPCP)$_4$-catalyzed reaction between vinyldiazoacetate (**5.36**) and nitrone (**5.30**) afforded the tricyclic product (**5.48**) in 42% yield and 84% ee. In the presence of wet pentane, the second rhodium carbene intermediate was captured by water, affording the isoxazolidine product (**5.49**) in 39% yield and 71% ee as a single diastereomer.



Scheme 5.11 Rh_2(*R*-DPCP)$_4$-catalyzed divergent and asymmetric synthesis

From these studies, the generation of a second rhodium carbene intermediate in the reaction is very likely by using either dirhodium triaryl or diarylcyclopropane carboxylate catalysts. The steric interaction between the *N*-aryl group and ligands around dirhodium triarylcyclopropane carboxylate catalyst could be too large to accommodate the *N*-aryl group to approach carbene site for cyclopropanation; instead, a hydride migration event took place followed by an alkene isomerization process to give formal [3+2]-annulation product. When the sterically less congested dirhodium diarylcyclopropane carboxylate catalyst was used, the steric hindrance between the *N*-aryl group and ligands was decreased, and an intramolecular cyclopropantion of the *N*-aryl group happened, leading to a cascade process to the tricyclic product; in the presence of water, the ylide formation with the second rhodium carbene would be much more fast than the intramolecular cyclopropanation of the *N*-aryl group, thus resulting the O-H insertion product.

The discovery of these highly selective transformation *via* tuning the catalyst and choosing proper reaction conditions opened up new possibilities for vinylogous transformations, especially the capture of the second rhodium carbene with a heteroatom nucleophile, functionalizing the vinyl group and carbenic center with construction of four chiral center in a single diastereo- and enantioselective step. Further optimization of the reactions *via* design of analogs of the dirhodium diarylcyclopropane carboxylate catalysts

and extension to other reacting partners could lead to a very useful three component coupling transformations.

5.3 Conclusion

In this chapter, a new type of vinylogous transformations of metallovinylcarbenes was developed. The use of sterically demanding dirhodium triarylcyclopropane carboxylate catalysts was crucial to the success in the vinylogous transformation of nitrone, generating the 2,5-dihydroisoxazole derivatives in highly enantioselective manner; the nitrones first served as a nucleophile to initiate the vinylogous attack, then it provided a second opportunity to capture the new rhodium species formed *in situ*. The rationale for the [3+2]-annulation in contrast to the previous [3+3]-annulation is due to the *s-trans* configuration of rhodium vinylcarbene. Importantly, through careful tuning the dirhodium catalysts and reaction conditions, different reaction pathways were made possible. The use of a sterically less demanding dirhodium diarylcyclopropane carboxylate catalyst in dry pentane led to a much more fast intramolecular cyclopropanation of the *N*-aryl ring than that of hydride migration at the second rhodium carbene stage, which then underwent a tandem sequence to afford a tricyclic product in highly stereoselective fashion; interestingly, when wet pentane was used in the later reaction, it opened up a new possibility for the second rhodium carbene species to react with water in a more fast approach than the cyclopropanation of the *N*-aryl ring. These studies once again underscored the unusual reactivity of the dirhodium cyclopropane carboxylate catalysts.

Chapter VI
Vinylogous Fluorination of Vinyldiazoacetates

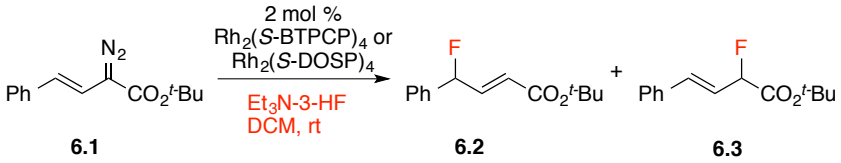
6.1 Introduction

The success of using bulky chiral dirhodium triarylcyclopropane carboxylate catalysts in asymmetric vinylogous transformations of rhodium vinylcarbenes led us to explore some other new possibilities of vinylogous functionalization. We became intrigued with the vinylogous fluorination of vinyldiazoacetates because this would lead directly lead to the synthesis of γ-fluoro-α,β-unsaturated carbonyls building blocks.

Selective fluorination methods are highly desirable as organofluorine compounds display broad utility as valuable pharmaceuticals, agrochemicals, materials and tracers for positron emission tomography.[61] γ-Fluoro-α,β-unsaturated carbonyls represent a versatile class of intermediates in organic synthesis and are prevalent motifs in biologically relevant compounds such as steroids, amino acids and metalloprotease inhibitors.[62] Traditional approaches for the synthesis of γ-fluoro-α,β-unsaturated carbonyls mainly rely on electrophilic fluorination of conjugated enol ethers[63] and Wittig-type reaction of α-fluoro aldehydes or ketones.[64]

The initial study was conducted by addition of a solution of styryldiazoacetate (**6.1**) to a solution of triethylamine trihydrofluoride[65] in dichloromethane, using sterically demanding R_2(*S*-BTPCP)$_4$ as catalyst (Scheme 6.1). Disappointingly, the reaction resulted in a very complex mixture and messy spots were observed from the TLC analysis. Further examination of the crude mixture with ^{19}F NMR found two sets of

quartet peaks that can be observed when the spectrum was expanded; the major peak is at -183.4 ppm. The product related to this peak would be the carbenic fluorinated product (**6.3**) since it is consistent with previous known fluorinated product.[66] The other very tiny peak is at -173.3 ppm, which was assigned as the vinylogous fluorination product (**6.2**) and was confirmed by the follow-up research in this Chapter. The use of Rh_2(*S*-DOSP)$_4$ also resulted in a messy reaction mixture, and analyzing the crude mixture by ^{19}F NMR indicated the existence of the same two very weak sets of quartet peaks, but the peak at -173.3 ppm is slightly bigger than the peak at -183.4 ppm. However, both reactions were hard to purify and no pure product was obtained.



6.1 **6.2** **6.3**

Scheme 6.1 Initial dirhodium catalysts evaluation in fluorination of vinyldiazoacetate

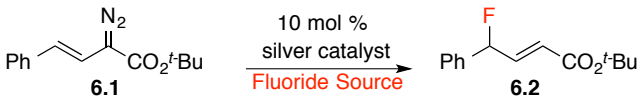
The failure of achieving a desired vinylogous fluorination with dirhodium catalysts led us to the consideration of other types of catalysts. The silver-catalyzed vinylogous transformations can be achieved with a variety of nucleophiles including alcohols, amines, and thiols,[67] and these products are not formed with dirhodium catalysts . Therefore, a study was conducted using silver catalysts for vinylogous fluorination of vinyldiazoacetate. The results are discussed in this Chapter.

6.2 Optimization studies

The use of silver catalysts was evaluated in the model reaction of styryldiazoacetate (**6.1**) and triethylamine trihydrofluoride. When silver acetate was used in the reaction, the desired vinylogous fluorinated product (**6.2**) was isolated in 90% yield (Table 6.1, entry

1). To seek a safer fluoride source, we then looked at some other nucleophilic fluoride reagents (Table 6.1, entries 2-9). Among the fluoride reagents examined, many of the standard nucleophilic fluoride sources failed to give any fluorinated products (Table 6.1, entries 2-7), but Deoxo-Fluor and DAST[68] can provide the desired product **360** in 44% and 55% yield, respectively (Table 6.1, entries 8, 9). After determining the effect of different silver salts (Table 6.1, entries 10-11), we chose silver acetate and triethylamine trihydrogen fluoride in dichloromethane as our standard fluorination conditions.

Table 6.1 Vinylogous fluorination optimizations



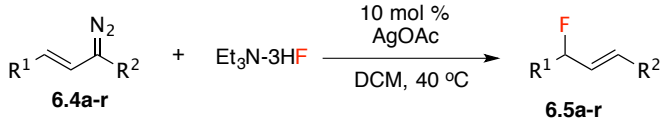
entry	catalyst	fluoride	yield (%)[b]
1	AgOAc	Et_3N-3HF	90
2	AgOAc	TBAF[c]	<5
3	AgOAc	TBABF	<5
4	AgOAc	KHF_2[d]	<5
5	AgOAc	Fluolead™	<5
6	AgOAc	TASF	<5
7	AgOAc	TMAF	<5
8	AgOAc	Deoxo-Fluor	44
9	AgOAc	DAST	55
10	$AgSbF_6$	Et_3N-3HF	88
11	AgOTf	Et_3N-3HF	90

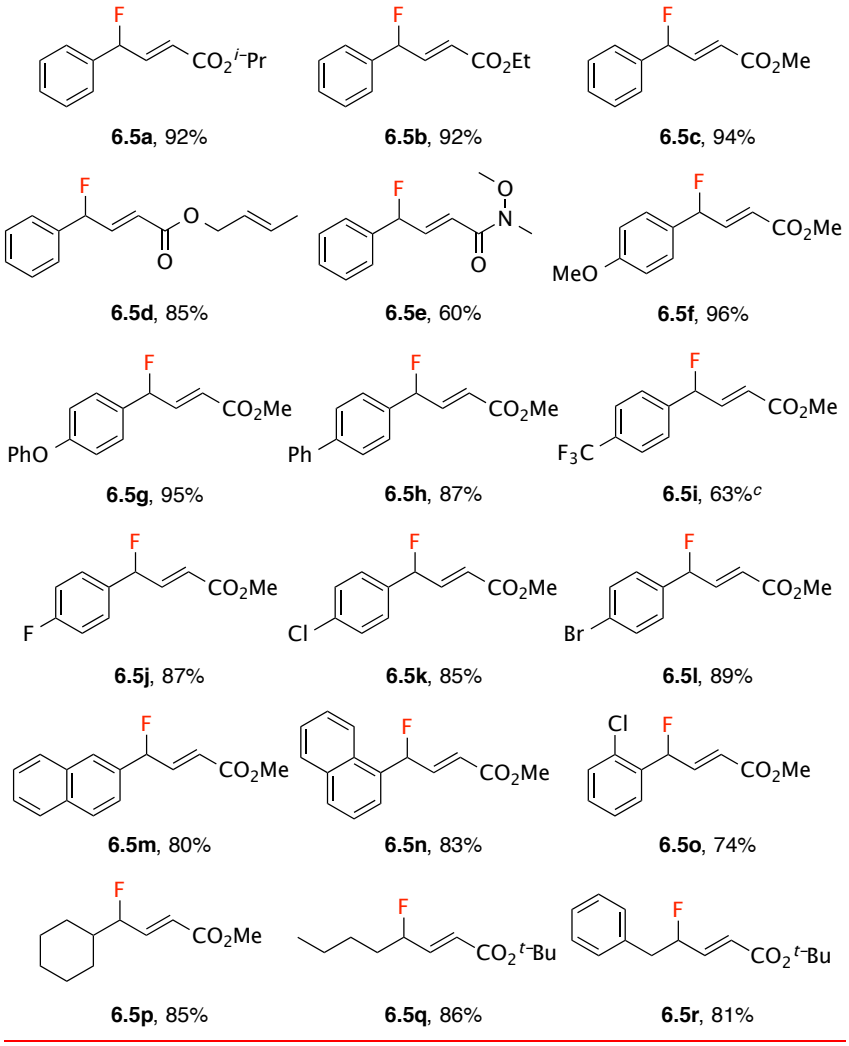
[a] Vinyldiazoacetate (0.4 mmol, 1.0 equiv.), silver catalyst (10 mol %), fluoride source (2.0 mmol, 5.0 equiv.), under reflux in dichloromethane. [b]Isolated yield, <5 refers to no observation of product (**6.2**) from ^{1}H NMR/^{19}F NMR analysis prior to chromatography. [c] 1.0 M in THF. [d] Dry DMF as solvent at 90 °C.

6.3 Scope of vinylogous fluorination of vinyldiazoacetates

Having developed the optimized conditions, the scope of the vinylogous fluorination was examined with a variety of vinyl diazo derivatives. The reaction was found to be quite general as illustrated in Table 6.2. The size of ester group (*tert*-butyl to methyl) did not affect the efficiency of this reaction, affording the desired products **6.5a-c** in high

Table 6.2 Synthesis of secondary allylic fluorides



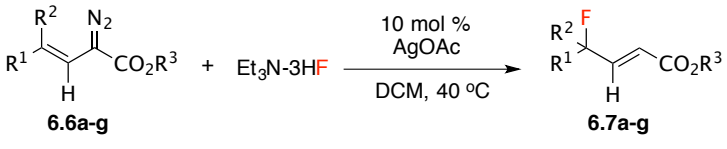


yields (92-94%). A particularly interesting example is the substrate with an allyl functional group on the ester (**6.4d**). The desired product (**6.5d**) was isolated in 85% yield and no intramolecular cyclopropanation was observed. Moreover, when an amide was used as the acceptor group (**6.4e**), the reaction can still afford the desired product (**6.5e**) in 60% isolated yield. The reaction can tolerate a variety of functionality on the aryl

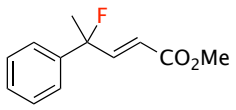
group as illustrated by **6.5f-o** (63-96%). Furthermore, the reaction can also be expanded to alkyl-substituted vinyldiazoacetates as seen from **6.5p-r** (81-86%).

To further evaluate the fluorination method, a series of 1,1-di-substituted vinyldiazoacetates (**6.6a-g**) were synthesized. When these vinyldiazoacetates were subjected to the standard conditions, the fluorinated products (**6.7a-g**) containing quaternary carbon-centers were readily formed in good to excellent yields (75-91%) with a variety of aryl- and alkyl-substituted vinyldiazoacetates (Table 5.11). A particularly interesting example is the synthesis of the fluorinated farnesol derivative (**6.7g**).

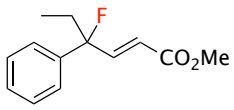
Table 6.3 Synthesis of tertiary allylic fluorides



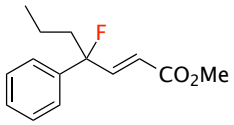
6.6a-g **6.7a-g**



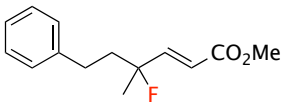
6.7a, 91%



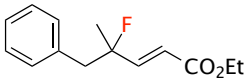
6.7b, 82%



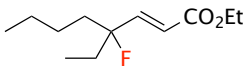
6.7c, 75%



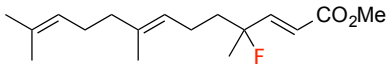
6.7d, 89%



6.7e, 80%



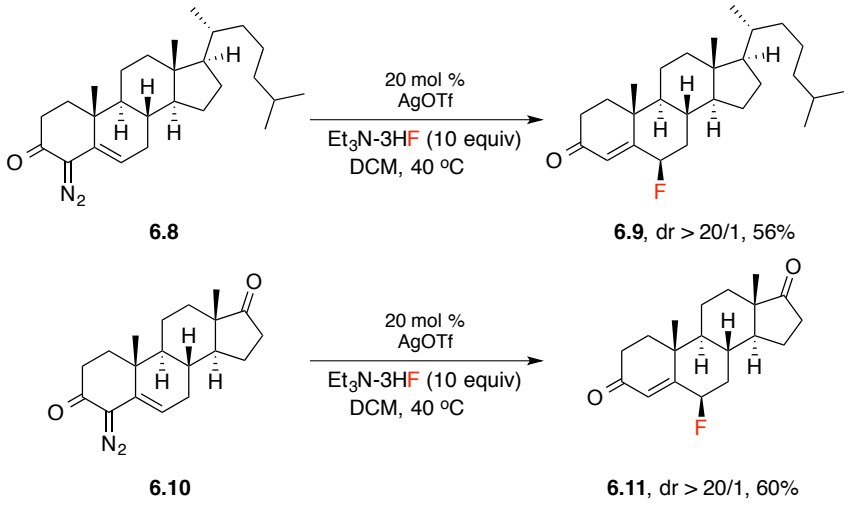
6.7f, 88%



6.7g, 85%

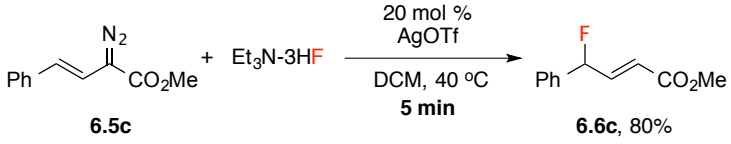
Fluorinated steroids constitute an important class of molecules with significant biological activity.[68] Therefore, we sought to develop a method for late-stage fluorination of steroids (Scheme 1). The steroidal derivatives (**6.8**) and (**6.10**) were readily formed by a diazo transfer reaction on the corresponding steroids. Under slightly modified reaction conditions using silver triflate, diazo (**6.8**) and (**6.10**) could be converted to the desired fluorinated steroids (**6.9**) and (**6.11**) in 56% and 60% yield, respectively. An intriguing

feature of this fluorination process is the selective formation of the 6-β-fluoro isomers. A similar selectivity has been seen in vinylogous hydroxylation of steroidal diazo *via* silver catalysis, in which stereoelectronic effects of the steroid diazo substrate control the diasteroselectivity.[67c]



Scheme 6.2 Late-stage fluorination of steroids

Considerable interest has been shown in developing fast fluorination methods because they may be useful in developing positron emission tomography (PET tracers with ^{18}F labeling, ^{18}F half-life: 110 min).[70] Metal-catalyzed reactions of diazo compounds can be extremely fast and accordingly we explored the possibility of achieving fast fluorination. Indeed, fluorination of vinyldiazoacetate (**6.6c**) in 80% isolated yield was achieved in 5 min when 20 mol% of silver triflate was used as catalyst (Scheme 6.3).



Scheme 6.3 Rapid fluorination of vinyldiazoacetate

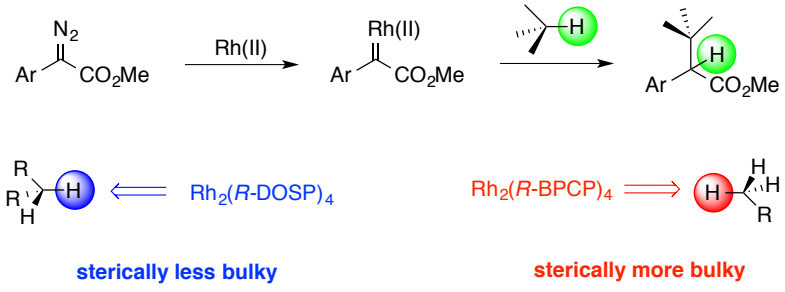
6.4 Conclusion

We have developed a silver-catalyzed vinylogous fluorination of vinyldiazoacetates. This novel methodology is operationally simple and provides a diverse range of γ-fluoro-α,β-unsaturated carbonyl building blocks. Importantly, the method offers a strategy for late-stage generation of fluorinated compounds that may be used in the synthesis PET radioligands. Future work will be directed to see whether an asymmetric version of this transformation could be achieved when chiral catalyst was used.

Chapter VII
Selective C–H Functionalization of Activated Primary C–H Bonds

7.1 Introduction

The combination of donor/acceptor diazoacetates and dirhodium tetraprolinate carboxylates illustrated by Rh_2(*R*-DOSP)$_4$ has been crucial for the development of highly selective intermolecular carbene C–H functionalization.[2] In general, this combination tends to favor C–H functionalization of secondary C–H bonds due to competing steric and electronic effects. The selective functionalization of primary C–H bonds even activated ones rather than secondary and/or tertiary C–H bonds have been a great challenge in carbene chemistry. A possible way to achieve this would be to use very bulky catalysts. Therefore, a systematic study was conducted to determine whether the chiral dirhodium triarylcyclopropane carboxylate catalysts would lead to the site selective functionalization of primary C–H bond in a complex molecule containing several types of C–H bonds (Scheme 7.1).



Scheme 7.1 Concept of catalyst-controlled site selective C–H functionalization

Intermolecular carbene C–H insertion is controlled by the structure of the carbene, the nature of the C-H substrate and the properties of the catalyst.[16] It was found that the more traditional acceptor-only and acceptor/acceptor metallocarbenes are very reactive, and are broadly useful for intramolecular C–H functionalization reactions. In contrast, the rhodium-bound donor/acceptor carbenes have attenuated reactivity compared to these conventional metallocarbenes, enabling highly selective intermolecular C–H functionalization to be achieved with a wide range of substrates (Figure 7.1).

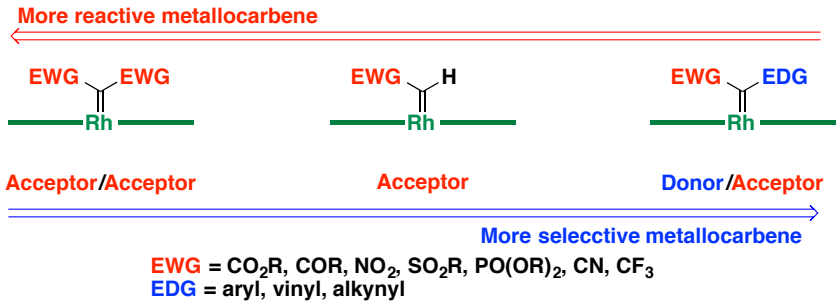
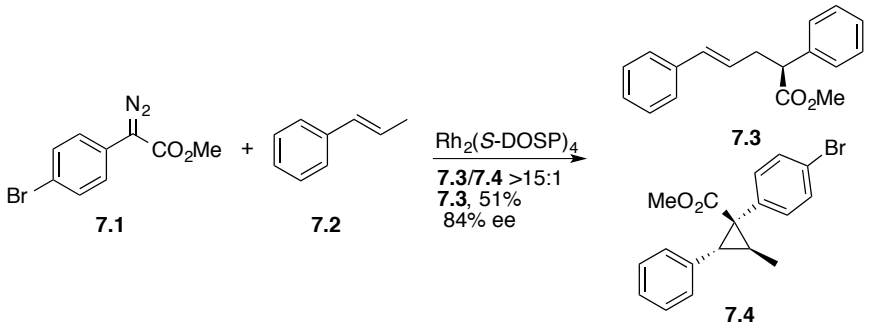


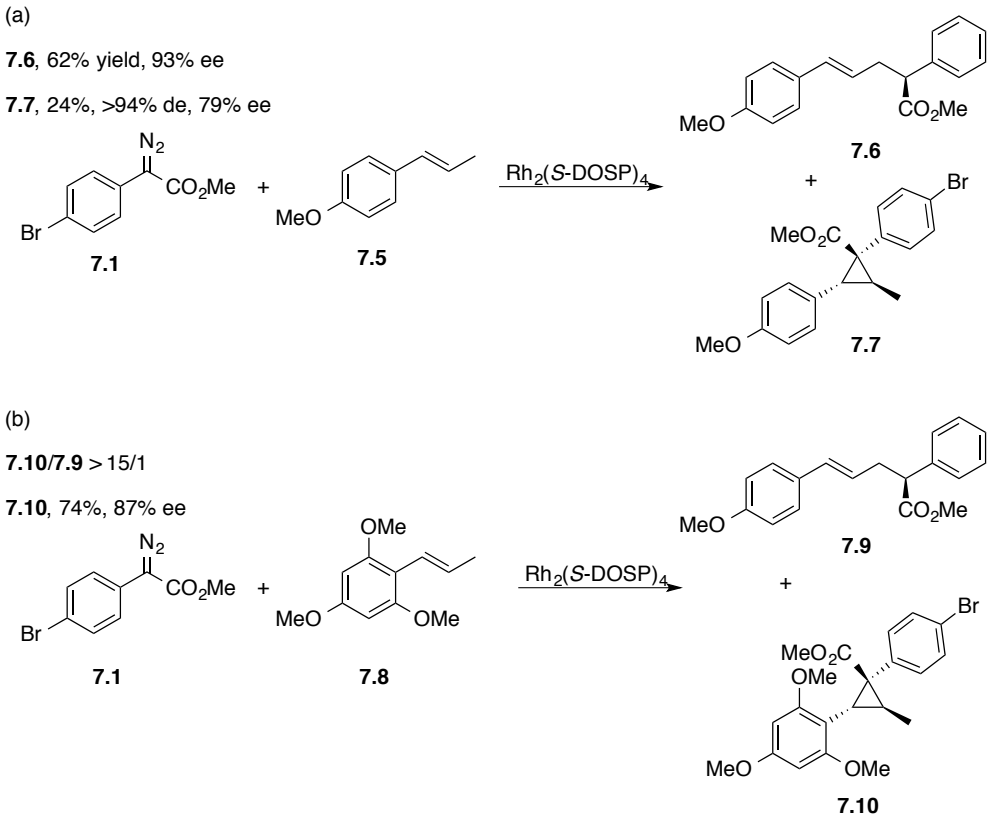
Figure 7.1 Reactivity and selectivity trends of rhodium carbenes

The steric and electronic effects of the substrate govern the dirhodium catalyzed selective C–H functionalization with donor-acceptor carbenoids. In terms of steric effects, reaction of a mono-substituted, 1,1-disubstituted and *cis*-1,2-disubstituted alkenes results almost exclusively in cyclopropanation, while the *trans*-1,2-disubstituted alkenes, underwent allylic C–H functionalization, illustrated by example in the Scheme 7.2.[71]



Scheme 7.2 The selectivity of *trans*-substituted alkene

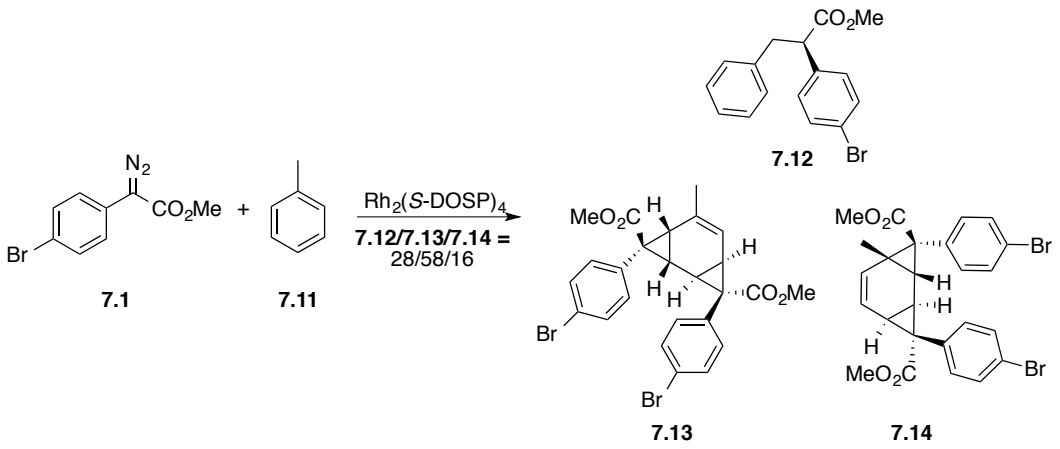
The electronic nature of the substituents surrounding the alkene also has a significant influence on the product distribution. For example, when electronic rich alkene (**7.5**) was used, the reaction resulted in a mixture of C-H insertion (**7.6**) and cyclopropanation product (**7.7**) (Scheme 7.3a). Using more electron-rich aryl group on *trans*-alkene further enhanced the cyclopropanation, as illustrated by the reaction between *trans*-alkene (**7.8**) and aryldiazoacetate (**7.1**)[71] (Scheme 7.3b).



Scheme 7.3 Electronic factor of *trans*-alkene in selective carbene transformations

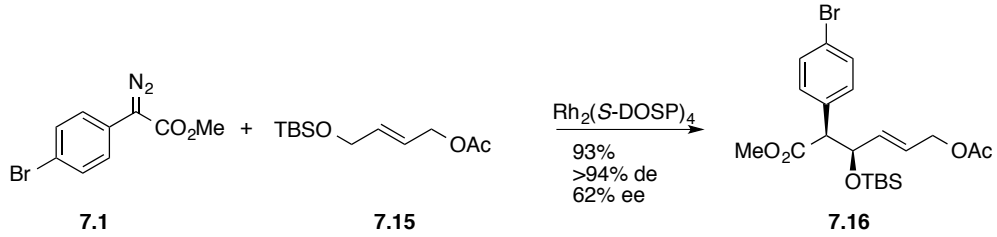
In particular, cyclopropanation of sterically accessible benzene derivatives could compete with C-H functionalization. For example, the reaction between aryldiazoacetate (**7.1**) and toluene gave a mixture of products[72] (Scheme 7.4). In addition to the benzylic C-H functionalization (**7.12**), double cyclopropanation products (**7.13**) and (**7.14**) were

also obtained. In this case, the cyclopropanation of benzene ring could be inhibited when a *para*-substitutent was installed in the toluene substrate.



Scheme 7.4 Example of competing cyclopropanation of benzene ring

Protecting groups can also be employed to control the selectivity in C-H functionalization. For example, in the reaction of diazoacetate (**7.1**) and substrate (**7.15**), the allylic C-H bonds that are close to an acetyl protecting group are electronically deactivated, therefore, the C-H functionalization event prefers the allylic site with a silyl ether protecting group, affording the product (**7.16**) in 93% yield[73] (Scheme 7.5).



Scheme 7.5 Protecting group effects in selective C–H functionalization

Another controlling element is the nature of dirhodium catalyst. In the reactions with the dirhodium tetraprolinate catalyst Rh_2(*R*-DOSP)$_4$, C–H functionalization is generally preferred at secondary C–H bonds, although a few examples of functionalization of sterically accessible tertiary C–H bonds[73] and electronically activated primary C–H

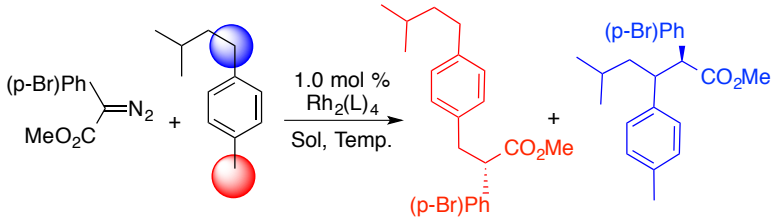
bonds[74] are known. In this chapter, we will describe a major change in the site selectivity of carbene-induced C–H functionalization using the bulky catalyst Rh_2(*R*-BPCP)$_4$, which results in a strong preference for reactions to occur at primary C–H bonds.

7.2 Results and discussion

7.2.1 Discovery and optimization

The reaction of methyl (4-bromophenyl)diazoacetate (**7.1**) with 4-isopentyltoluene (**7.17**) was used for the initial evaluation of the role of bulky catalysts because (**7.17**) contains several types of C–H bonds. The results are summarized in Table 7.1. When the established catalysts, Rh_2(*R*-DOSP)$_4$ and Rh_2(*S*-PTAD)$_4$ were used, the reaction resulted in a mixture of benzylic C–H functionalization products (**7.18**) and (**7.19**). In contrast, the triphenylcyclopropane carboxylate catalyst Rh_2(*R*-TPCP)$_4$ switched the selectivity towards primary benzylic C–H bonds, providing (**7.17**) in 86% yield and 76% ee (Table 7.1, entry 3). Further examination of related catalysts revealed that the biphenyl derivative Rh_2(*R*-BPCP)$_4$ gave the highest level of enantioselectivity, generating (**7.18**) in 94% ee (Table 7.1, entry 5). Additional optimization of solvents revealed that Rh_2(*R*-BPCP)$_4$ retained high enantioselectivity when trifluorotoluene and dichloromethane were used as solvent (Table 6.2, entries 6 and 7), which is different from the general behavior of Rh_2(*R*-DOSP)$_4$ and Rh_2(*S*-PTAD)$_4$. Furthermore, good yields of (**7.18**) could be obtained with just 1.2 equiv. of (**7.17**) and 0.5 mol% of Rh_2(*R*-BPCP)$_4$. Indeed, the enantioselectivity was still unchanged when only 0.1 mol% of Rh_2(*R*-BPCP)$_4$ was used but under these conditions, the yield of (**7.18**) was lower (Table 7.1, entry 11). It is noted that the use of dichloromethane rather than the expensive 2,3-dimethylbutane and only 1.2 equiv. of the substrate adds a practical value for this reaction.

Table 7.1 Initial studies on selective C–H functionalization



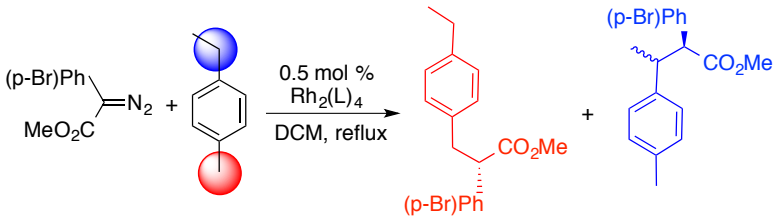
7.1 **7.17** **7.18** **7.19**

entry	catalyst	solvent	(eq.) **7.17**	ratio **7.18**:**7.19**	yield (%)[a]	ee (%) **7.18**
1	Rh_2(*R*-DOSP)$_4$	DMB	5.0	1:1.7	70	77
2	Rh_2(*S*-PTAD)$_4$	DMB	5.0	1.1:1	73	70
3	Rh_2(*R*-TPCP)$_4$	DMB	5.0	>20:1	86	76
4	Rh_2(*R*-BTPCP)$_4$	DMB	5.0	>20:1	90	90
5	Rh_2(*R*-BPCP)$_4$	DMB	5.0	>20:1	90	94
6[b]	Rh_2(*R*-BPCP)$_4$	$PhCF_3$	5.0	>20:1	84	89
7	Rh_2(*R*-BPCP)$_4$	DCM	5.0	>20:1	87	94
8	Rh_2(*R*-BPCP)$_4$	DCM	2.0	>20:1	84	95
9	Rh_2(*R*-BPCP)$_4$	DCM	1.2	>20:1	84	95
10[c]	**Rh_2(*R*-BPCP)$_4$**	**DCM**	**1.2**	>20:1	**82**	**95**
11[d]	Rh_2(*R*-BPCP)$_4$	DCM	1.2	>20:1	63	95

[a] Isolated yield of **7.18**, yields in entry 1 and 2 refer to the combined yiel . [b] 55 °C internal temperature. [c] 0.5 mol% catalyst loading. [d] 0.1 mol% catalyst loading.

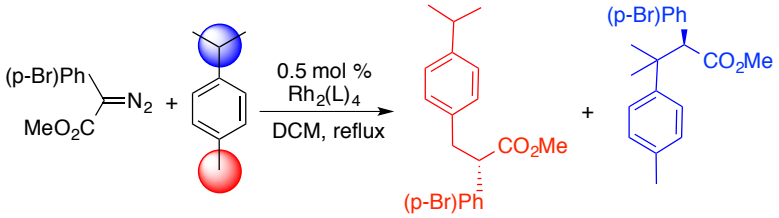
7.2.2 Substrate scope in selective C–H bond functionalization

We subsequently explored the influence of Rh_2(*R*-BPCP)$_4$ with more challenging substrates (Scheme 7.6) The Rh_2(*R*-DOSP)$_4$-catalyzed reaction of 4-ethyltoluene (**7.20**) is known to occur selectively at the secondary benzylic site (**7.21**:**7.22** < 1:20).[9a] In contrast, the Rh_2(*R*-BPCP)$_4$-catalyzed reaction favors C–H functionalization at the primary C–H bond (**7.21**:**7.22** = 5:1) in a 74% combined isolated yield, with (**7.21**) produced in 92% ee. Another challenging substrate is isopropyl toluene (**7.23**), which under Rh_2(*R*-DOSP)$_4$-catalyzed reaction gave a mixture of primary/tertiary C–H functionalization (**7.24**:**7.25** = 1:4). However, when Rh_2(*R*-BPCP)$_4$ was used, the primary C–H functionalization product (**7.24**) was selectively formed (**7.24**:**7.25** > 20:1) in 75% isolated yield and 97% ee.



7.1 **7.20** **7.21** **7.22**

catalyst	ratio **7.21:7.22**	yield (%)	ee (%) **7.21**
Rh_2(*R*-DOSP)$_4$	**<1:20**	75	-
Rh_2(*R*-BPCP)$_4$	**5:1**	74[a]	92



7.1 **7.23** **7.24** **7.25**

catalyst	ratio **7.24:7.25**	yield (%)	ee (%) **7.24**
Rh_2(*R*-DOSP)$_4$	**1:4**	72[a]	73
Rh_2(*R*-BPCP)$_4$	**>20:1**	75	97

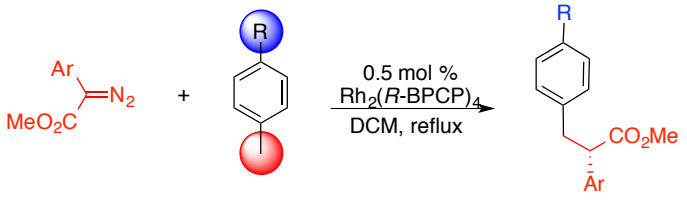
[a]Combined yield

Scheme 7.6 C–H Functionalization of ethyltoluene and isopropyltoluene

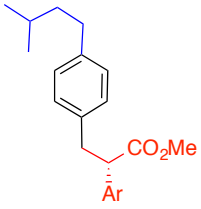
To probe the generality of this catalyst in selective primary C–H bond functionalization with donor/acceptor carbenoid intermediates, various combinations of aryldiazoacetates with alkanes bearing different C–H bonds were evaluated. The results are summarized in Table 7.2. The reaction proceeded smoothly when different donor groups were used and provided the desired products in decent yields and high regioselectivity (>20:1, 1°) and high enantioselectivity (>90% ee) as can be seen from products (**7.28a-c**); however, the *meta*-bromophenyl group erodes the asymmetric induction (**7.28d**, 77% ee). Even though the Rh_2(*R*-BPCP)$_4$-catalyzed reaction of (**7.1**) with ethyltoluene gave a mixture of primary and secondary C–H insertion products, when the secondary site was slightly

larger such as *iso*-butyl, *n*-butyl, and even *n*-propyl, the reaction was highly site selective as illustrated

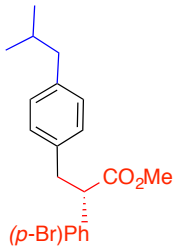
Table 7.2 Selective C–H functionalization of toluene derivatives



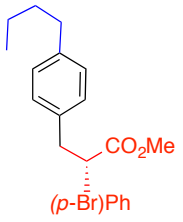
7.1, **7.26a-d** **7.17**, **7.27a-h** **7.28a-m**



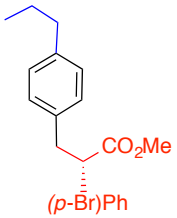
Ar = Ph, 62%, 92% ee, **7.28a**
Ar = (*p*-F)Ph,70%, 90% ee, **7.28b**
Ar = (*p*-TfO)Ph,73%, 90% ee, **7.28c**
Ar = (*m*-Br)Ph, 86%, 77% ee, **7.28d**



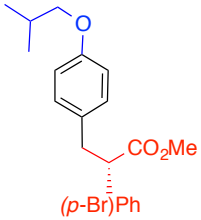
7.28e, 88%, 95% ee



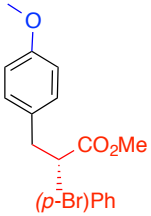
7.28f, 86%, 96% ee



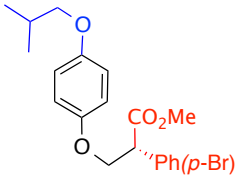
7.28g, 83%, 96% ee



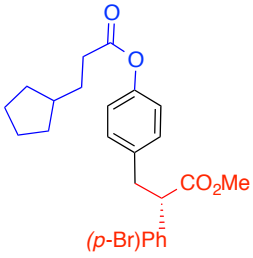
7.28h, 85%, 91% ee



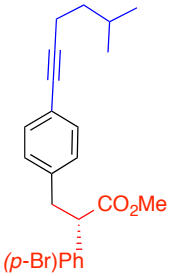
7.28i, 85%, 90% ee



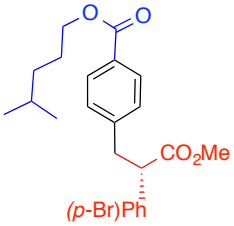
7.28j, 68%, 90% ee



7.28k, 58%, 95% ee



7.28l, 66%, 94% ee



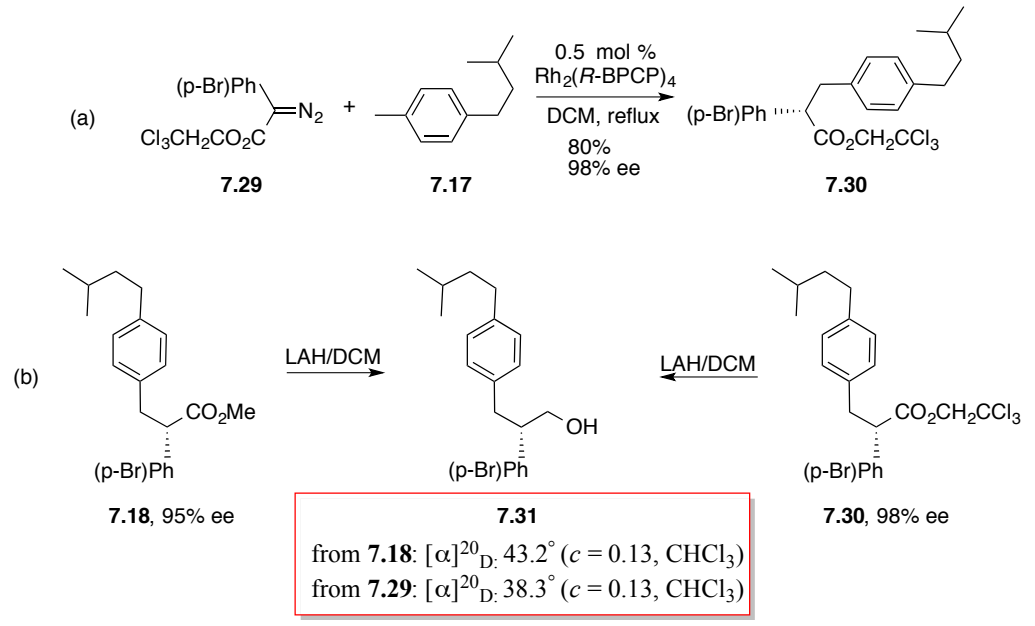
7.28m, 38%, 94% ee

by products (**7.28e-g**) (>20:1 1°, 95-96% ee). It was expected that the site selectivity would be more challenging in the systems containing competing methoxy and *iso*-butoxy groups, but once again products (**7.28h-i**) were cleanly formed (>20:1 1°, 90-91% ee). In terms of substrate containing methoxy and isobutoxy, the reaction gave a clean C–H

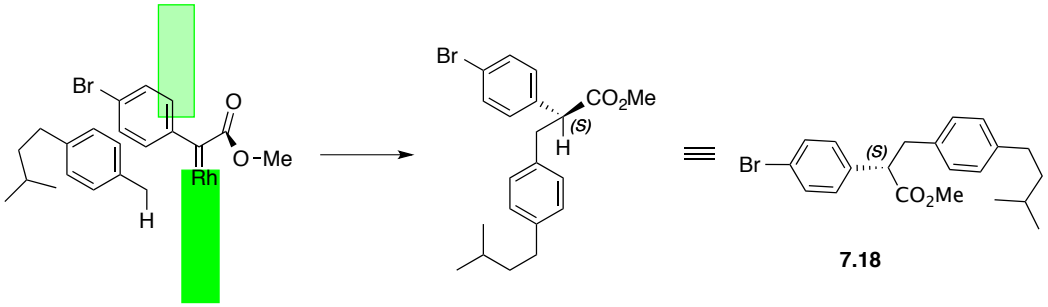
functionalization on primary methoxy, as seen from result in product (**7.28j**). The reaction was compatible with alkyne and ester functional groups as illustrated for (**7.28k-l**) (>20:1 1°, 94-95% ee), but the yield of the ester derivative (**7.28m**) was only 38%, presumably because the primary methyl group is not as activated on account of the electron withdrawing ester functionality.

One of the challenges associated this project was the determination of the absolute configuration of the C-H functionalization products. All attempts at obtained crystalline material of the methyl ester products were unsuccessful. Fortunately, a parallel study by Mr. David Guptill using the trichloroethyl esters derivatives revealed that the C-H functionalization products were much more crystalline than the corresponding methyl ester derivatives. Consequently, an effort was made to use Guptill's protocol to obtain crystalline material in products related to this C-H functionalization study. Reaction of a sample of trichloroethyl *para*-bromophenyldiazoacetate (**7.29**), supplied by Guptill, with 1-isopentyl-4-methylbenzene (**7.17**) resulted in the formation of product (**7.30**) in 98% ee as a crystalline product (Scheme 7.7a). The very high enantioselectivity is consistent with the results observed by Guptill. The absolute configuration of the trichloroethyl-derived product (**7.30**) was determined by X-ray crystallography; to confirm the methyl ester derivative (**7.18**) has the same absolute configuration as the trichloroethyl ester-derived product (**7.30**), both (**7.18**) and (**7.30**) were reduced to the corresponding alcohol (**7.31**), which has a comparable positive optical rotation (Scheme 7.7b). The absolute configuration of the other products was assigned by analogy. The absolute configuration in these products is in agreement with the predictive model developed for the face

selectivity of dirhodium tetrakis(triarylphenylcyclopropane carboxylate)-catalyzed carbene reactions (Scheme 7.8).[75]

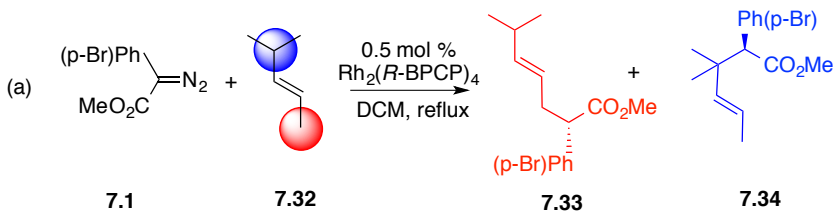


Scheme 7.7 Confirmation of absolute configuration with methyl ester derivative



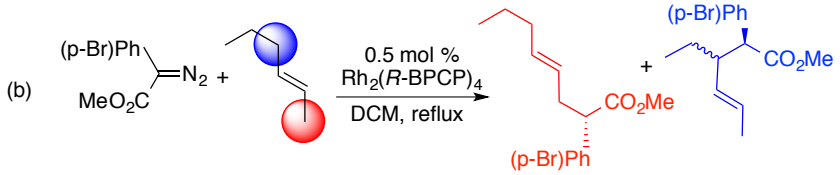
Scheme 7.8 Absolute stereochemistry rationale by predictive model

Having established that Rh_2(*R*-BPCP)$_4$ enhances C–H functionalization of primary benzylic C–H bonds, studies were then conducted to determine if the same trend would be seen for allylic C–H functionalization (Scheme 7.9). The Rh_2(*R*-DOSP)$_4$-catalyzed reaction of aryldiazoacetate (**7.1**) and (*E*)-4-methylpent-2-ene (**7.32**) produced a mixture of C–H functionalization products, favoring the tertiary C–H insertion product (**7.34**) in poor enantioselectivity (48% ee); however, Rh_2(*R*-BPCP)$_4$ switched the selectivity



7.1 **7.32** **7.33** **7.34**

catalyst	ratio **7.33**:**7.34**	yield (%)	ee (%) **7.33**
Rh_2(*R*-DOSP)$_4$	**1:7**	81[a]	-
Rh_2(*R*-BPCP)$_4$	**17:1**	60	94



7.1 **7.35** **7.36** **7.37**

catalyst	ratio **7.36**:**7.37**	yield (%)[a]	ee (%) **7.36**
Rh_2(*R*-DOSP)$_4$	**1:9**	75	-
Rh_2(*R*-BPCP)$_4$	**8:1**	80	95

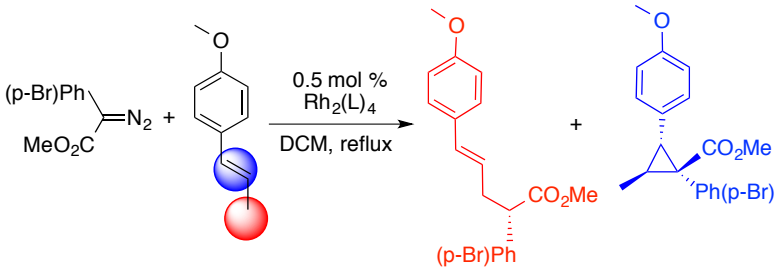
[a]Combined yield

Scheme 7.9 C–H functionalization of (*E*)-4-methylpent-2-ene and (*E*)-2-hexene

towards the primary C–H bond and strongly favored the formation of (**7.33**) (**7.33**:**7.34** = 17:1, 94% ee, Scheme 7.9a). The same trend of selectivity was also seen with 2-hexene (**7.35**) (Scheme 7.9b). Rh_2(*R*-BPCP)$_4$-catalyzed reaction prefers to give product (**7.36**) in high enantioselectivity (95% ee) while Rh_2(*R*-DOSP)$_4$-catalyzed transformation favors the vinyl methylene site, providing a mixture of diastereomers (**7.37**).

In certain cases, Rh_2(*R*-DOSP)$_4$-catalyzed reactions can lead to a mixture of C–H functionalization and cyclopropanation products. Therefore, it became of interest to determine whether Rh_2(*R*-BPCP)$_4$ would influence the chemoselectivity of such system. One example that leads to a mixture is the Rh_2(*R*-DOSP)$_4$-catalyzed reaction of (**7.1**) with *trans*-anethole (**7.5**), which generated a 5:1 mixture of the C-H insertion (**7.6**) and cyclopropanation (**7.7**) products (Scheme 7.10). A previous report indicated that the use of a sterically congested dirhodium catalyst Rh_2(TPA)$_4$ could improve the selectivity

toward primary C–H insertion (**7.6**:**7.7** >15:1) in 2,3-dimethylbutane. When the reaction was conducted using Rh_2(*R*-BPCP)$_4$ as catalyst, the chemoselectivity has the same trend, providing the primary C–H insertion product in 85% isolated yield and 88% ee (**7.6**:**7.7** = 16:1).

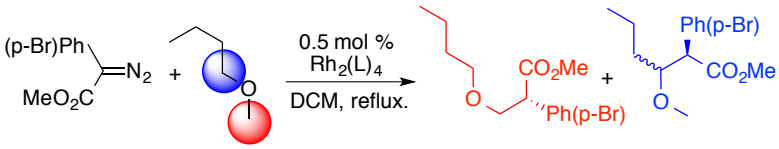


7.1 **7.5** **7.6** **7.7**

catalyst	ratio **7.6**:**7.7**	yield (%)	ee (%) **7.6**
Rh_2(*R*-DOSP)$_4$	**5:1**	76[a]	76
Rh_2(*R*-BPCP)$_4$	**16:1**	85	88

[a]Combined yield

Scheme 7.10 C–H functionalization of *trans*-anethole



7.1 **7.38** **7.39** **7.40**

catalyst	ratio **7.39**:**7.40**	yield (%)	ee (%) **7.39**
Rh_2(*R*-DOSP)$_4$	**3:2**	77[a]	61
Rh_2(*R*-BPCP)$_4$	**>20:1**	86	64

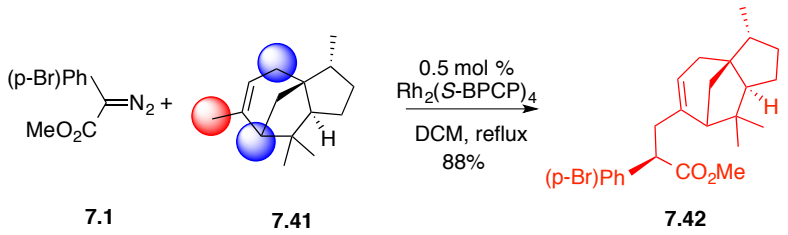
[a] Combined yield

Scheme 7.11 C–H functionalization of 1-methoxybutane

Enhanced site selectivity was also observed with unsymmetrical ethers (Scheme 7.11). The Rh_2(*R*-DOSP)$_4$-catalyzed reaction of (**7.1**) with methyl butyl ether (**7.38**) gave a mixture of (**7.39**) and (**7.40**). In contrast, the Rh_2(*R*-BPCP)$_4$-catalyzed reaction dramatically improved the selectivity for the primary C–H bond (>20:1), affording the

product (**7.39**) in high yield (86%), but with relatively moderate enantioselectivity (64% ee).

To challenge the high selectivity of $Rh_2(BPCP)_4$, (-)-α-cedrene (**7.41**) was considered to be an interesting substrate because it contains primary, secondary and tertiary allylic C–H bonds (Scheme 7.12). The Rh_2(*S*-BPCP)$_4$-catalyzed reaction of (**7.1**) with (**7.41**) proceeded cleanly and afforded the primary allylic C–H functionalization product (**7.42**) in 88% yield as a single diastereomer. No other regioisomers were observed in the ^{1}H NMR of the crude reaction mixture. The absolute configuration of (**7.42**) was determined by X-ray crystallography. The asymmetric induction observed in the formation of the new stereogenic center in (**7.42**) is consistent with what had been seen in (**7.18**), supporting the tentative assignments of the absolute configurations of the other products by analogy.

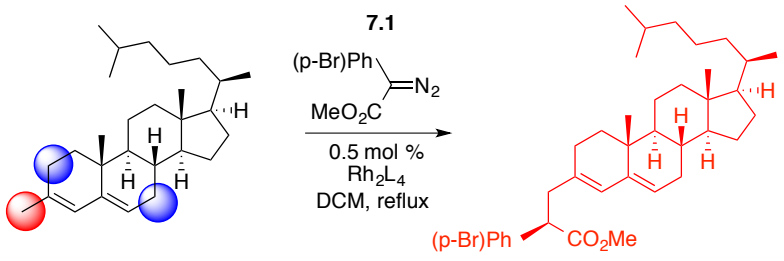


7.1 **7.41** **7.42**

Scheme 7.12 Selective C–H functionalization of (-)-α-cedrene

A study was also conducted on the steroid derivative (**7.43**) (Scheme 7.13). Even though (**7.43**) has three allylic sites, the two secondary allylic sites contained within the steroid framework are sterically inaccessible for both the $Rh_2(DOSP)_4$ and $Rh_2(BPCP)_4$ catalysts. However, the primary C–H functionalization is still influenced by the nature of the catalyst. In the Rh_2(*R*-DOSP)$_4$-catalyzed reactions, a 3:1 mixture of diastereomers were formed, whereas the Rh_2(*S*-DOSP)$_4$-catalyzed reaction appears to be the matched reaction because (**7.44**) was formed in a 16:1 mixture, favoring the opposite diastereomer. The chiral influence is more pronounced with the $Rh_2(BPCP)_4$ catalysts. The Rh_2(*R*-

BPCP)$_4$-catalyzed reaction gave a 6:1 mixture of diastereomers, while Rh$_2$(*S*-BPCP)$_4$-catalyzed reaction gave a > 20:1 of the opposite diastereomer (**7.44**), which can be isolated in 96% yield. The absolute configuration of the new stereogenic center generated in the matched reactions was tentatively assigned as (*R*) by analogy.



7.43 **7.44**

catalyst	dr	yield (%)[a]
Rh$_2$(*R*-DOSP)$_4$	1:3	82
Rh$_2$(*S*-DOSP)$_4$	16:1	86
Rh$_2$(*R*-BPCP)$_4$	1:6	89
Rh$_2$(*S*-BPCP)$_4$	**>20:1**	96

[a] Combined yield of the two diasteromers for the top three entries.

Scheme 7.13 Late-stage C–H functionalization of steroid

7.3 Conclusion

This chapter describes the control experiments on site selective C-H functionalization with Rh$_2$(*R*-DOSP)$_4$ and Rh$_2$(*R*-BPCP)$_4$. The Rh$_2$(*R*-DOSP)$_4$, catalyzed reactions of aryldiazoacetates cause preferential C–H functionalization at secondary C–H bonds due to competing steric and electronic effects. When it comes to molecules containing different sets of C–H bonds, the reaction generated a mixture of C–H functionalization products with low levels of stereocontrol. The sterically more demanding dirhodium tetrakis(triarylcyclopropane-carboxylate) catalysts exemplified by Rh$_2$(*R*-BPCP)$_4$ did a much more selective C-H functionalization of primary C–H bonds at benzylic, allylic and methoxy position in the presence of some other type of C–H bonds. Notably, this

new method was applied to late-stage C–H functionalization of activated primary C–H bond in natural product (-)-α-cedrene and a steroid, in which the enantiomer of Rh_2(*R*-BPCP)$_4$ was found to be the matched catalyst to achieve high level of stereocontrol. These early studies on catalyst-controlled selective C–H functionalization set a good foundation to realize the goal on selective manipulation of different C–H bonds in complex molecules with a 'toolbox' of catalysts in the future.

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Experimental Section

General methods and reagents

All experiments were performed under anhydrous conditions in an atmosphere of argon except where stated, using flame-dried glassware. Solvents were obtained from drying columns (Grubbs type solvent purifier) except acetone and ethyl acetate (dried over calcium hydride under reflux and kept under argon atmosphere and 4 Å molecular sieves). Unless otherwise noted, all other reagents were obtained from commercial sources and used as received. ^{1}H Nuclear Magnetic Resonance (NMR) spectra were recorded at 400 or 600 MHz. Data are presented as follows: chemical shift (in ppm on the δ scale relative to δH 7.27 for the residual protons in $CDCl_3$ or δH 7.15 for the residual protons in C_6D_6), multiplicity (s = singlet, d = doublet, t = triplet, q = quartet, m = multiplet, br = broad), coupling constant (*J*/Hz), integration. Coupling constants were taken directly from the spectra and are uncorrected. ^{13}C NMR spectra were recorded at 100 or 150 MHz, and all chemical shift values are reported in ppm on the δ scale, with an internal reference of δC 77.0 for $CDCl_3$ or δC 128.39 for C_6D_6. ^{19}F NMR spectra were recorded at 376.3 MHz, using trichlorofluoromethane as an internal standard ($CFCl_3$, δ =0.0). Mass spectral determinations were carried out by using APCI, ESI or EI as ionization source. Melting points are uncorrected. Infrared spectral data are reported in units of cm^{-1}. Analytical TLC was performed on silica gel plates using UV light or potassium permanganate and phosphomolybdic acid as stains. Flash column chromatography was performed on silica gel 60Å (230-400 mesh). Optical rotations were measured on Jasco polarimeters. Analytical enantioselective chromatographies were

measured on Varian Prostar instrument and used isopropanol/hexane as gradient. As for the important ligands, new dirhodium carboxylate catalysts and novel diazo compounds, the detailed procedures are summarized in each chapter.

Experimental Data for Chapter II

General procedure for Rh(II)-catalyzed cyclopropanation of alkenes

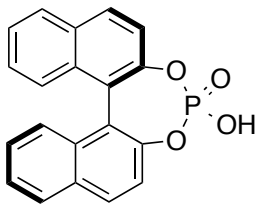
A flame-dried 25 mL flask was charged with the dirhodium complex (0.01 equiv), and the flask was flushed with argon for 15 minutes, then degassed toluene (2 mL) was injected, followed by addition of alkene (5.0 equiv) under argon condition. After 5 minutes, methyl aryl- or vinyl diazoacetate (0.5 mmol, 1.0 equiv) in degassed toluene (4 mL) was added over one hour by syringe pump under argon atmosphere at room temperature. The reaction went for another half an hour after dropping. The mixture was concentrated under reduced pressure and purified by flash column chromatography (hexanes/ethyl acetate) in silica gel to provide the products.

General procedure for Rh(II)-catalyzed C–H insertion reaction

A flame-dried 25 mL flask was charged with the dirhodium complex (0.01 equiv), and the flask was flushed with argon for 15 minutes, then degassed toluene (2 mL) was injected, followed by addition of 1,4-cyclohexadiene (5.0 equiv) under argon atmosphere. After 5 minutes, methyl aryl- or vinyl diazoacetate (0.5 mmol, 1.0 equiv) in degassed toluene (4 mL) was dropped for one hour under argon atmosphere at room temperature. The reaction went for another half an hour after dropping. The mixture was concentrated under reduced pressure and purified by flash column chromatography in silica gel (hexanes/ethyl acetate) to provide the products.

Procedure for the synthesis of *R*-binaphtholphosphate

Under argon atmosphere, commercially available, enantiomerically pure *R*-binaphthol (2.0 g, 7.0 mmol) was dissolved into anhydrous pyridine (20 mL), and phosphoryl trichloride (0.98 mL, 10.5 mmol) was slowly added, and then, the mixture was heated to reflux for 3 hours. The reaction was cooled to room temperature, and pure water (2.0 mL) was added, and the flask was then heated to reflux for another 3 hours. After that, the pyridine was completely removed overnight on vacuum pump and 6N HCl (30 mL) was added, and the resulting solution was heated to reflux for 3.0 hours. The reaction was then cooled to room temperature and was filtrated to get the desired product and dried over P_2O_5 in decicator overnight to get a colorless powder compound (**2.27**) (2.23g, 92%).



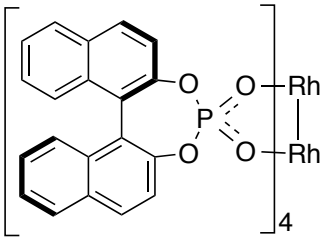
(*R*)-4-hydroxydinaphtho[2,1-d:1',2'-f][1,3,2]dioxaphosphepine 4-oxide (**2.27**)

^{1}H NMR (400 MHz, CD_3OD): δ 8.09 (d, *J* = 8.8 Hz, 2H), 7.99 (d, *J* = 8.4 Hz, 2H), 7.54 (d, *J* = 8.8 Hz, 2H), 7.49-7.45 (m, 2H), 7.29-7.27 (m, 4H). The NMR spectrum is consistent with previously reported data.[1]

Procedure for the synthesis of Rh_2(*R*-BNP)$_4$

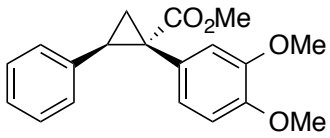
[1] Hodgson, D.M.; Selden, D. A.; and Dossetter, A. G. *Tetrahedron: Asymmetry* **2003**, *14*, 3841.

To a 50 mL flask was fitted with a Soxhlet extractor containing a 1:1 mixture of sand and Na_2CO_3, was added (*R*)-binaptholhydrogen phosphate (1.4 g, 4.0 mmol), $Rh_2(OAc)_4$ (0.13 g, 0.29 mmol), and 25 mL of anhydrous chlorobenzene, the reaction was refluxed at 150-160 °C for 36 h. Then, the chlorobenzene was removed and the residue was dissolved in dichloromethane (50 mL) and filtration to recover the excess ligand. The solution was dried and recrystalized (dichloromethane/hexane) to get a yellow-green solid (**2.28**) (200 mg, 44%).



tetrakis-[(*R*)-4-hydroxydinaphtho[2,1-d:1',2'-f][1,3,2]dioxaphosphepine 4-oxide]dirhodium catalyst, Rh_2(*R*-BNP)$_4$ (**2.28**)

^{1}H NMR (400 MHz, CD_3OD): δ 7.86 (dd, *J* = 15.2 and 8.0 Hz, 4H), 7.60 (d, *J* = 9.2 Hz, 2H), 7.46 (t, *J* = 7.6 Hz, 4H), 7.30-7.29 (m, 2H). The NMR spectrum is consistent with previously reported data.[2]

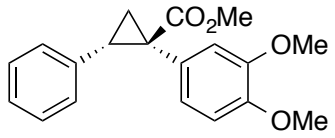


(1*S*,2*R*)-methyl 1-(3,4-dimethoxyphenyl)-2-phenylcyclopropanecarboxylate (**2.30**)

[2] Pirrung M. C.; Zhang J. *Tetrahedron Lett.* **1992**, *33*, 5987.

Prepared according to the general procedure for Rh(II)-catalyzed cyclopropanation of alkenes using methyl 2-diazo-2-(3,4-dimethoxyphenyl)acetate (**2.29**) (118 mg, 0.5 mmol, 1.0 equiv) and styrene (**2.2**) (260 mg, 2.5 mmol, 5.0 equiv) with Rh_2(*R*-BNP)$_4$ (8.0 mg, 1 mol%) at room temperature, and purified by flash column chromatography (hexanes/ethyl acetate = 20/1) to give the product (**2.30**) as a white solid (114.8 mg, 93%).

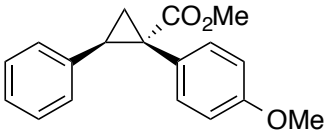
Mp 88-89 ^oC; [α] $^{20}_{D.}$ 28.4^o (*c* = 1.51, $CHCl_3$); ^1H NMR (400 MHz, $CDCl_3$): δ 7.08-7.06 (m, 3H), 6.80-6.78 (m, 2H), 6.67-6.66 (m, 2H), 6.36 (s, 1H), 3.79 (s, 3H), 3.67 (s, 3H), 3.55 (s, 3H), 3.07 (dd, *J* = 9.2, 7.6 Hz, 1H), 2.13 (dd, *J* = 9.2, 4.8 Hz, 1H), 1.84 (dd, *J* = 7.2, 4.8 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 174.5, 147.8, 136.4, 127.9, 127.7, 127.2, 126.3, 123.9, 115.3, 110.2, 55.5, 52.6, 36.9, 33.1, 29.6, 20.8; IR (film): 2924, 1716, 1518, 1455, 1434, 1413, 1341, 1229, 1208, 1177; HRMS (ESI) calcd for $C_{19}H_{21}O_4$ $(M+H)^+$ 313.14398 found 313.14332; HPLC: (Chiralcel OD-H, 6% isopropanol in hexane, 1.0 mL/min, 1 mg/mL, 30 min, UV 254 nm) retention times of 14.7 min (minor) and 18.4 min (major), 94% ee.



(1*R*,2*S*)-methyl 1-(3,4-dimethoxyphenyl)-2-phenylcyclopropanecarboxylate (***S*-2.30**)

Prepared according to the general procedure for Rh(II)-catalyzed cyclopropanation of alkenes using methyl 2-diazo-2-(3,4-dimethoxyphenyl)acetate (**2.29**) (23.6 mg, 0.1 mmol, 1.0 equiv) and styrene (**2.2**) (52 mg, 0.5 mmol, 5.0 equiv) with Rh_2(*S*-CBNP)$_4$ (1.6 mg, 1 mol%) at room temperature, and purified by flash column chromatography (hexane/ethyl

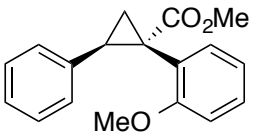
acetate = 20/1) to give product (*S*-**2.30**) as a white solid (21 mg, 67%). HPLC: (Chiralcel OD-H, 6% isopropanol in hexane, 1.0 mL/min, 1 mg/mL, 30 min, UV 254 nm) retention times of 14.7 min (minor) and 18.4 min (major), 70% ee.



(1*S*,2*R*)-methyl 1-(4-methoxyphenyl)-2-phenylcyclopropanecarboxylate (**2.32a**)

Prepared according to the general procedure for Rh(II)-catalyzed cyclopropanation of alkenes using methyl 2-diazo-2-(4-methoxyphenyl)acetate (**2.31a**) (90 mg, 0.5 mmol, 1.0 equiv) and styrene (**2.2**) (260 mg, 2.5 mmol, 5.0 equiv) with Rh_2(*R*-BNP)$_4$ (8.0 mg, 1 mol%) at room temperature, and purified by flash column chromatography (hexanes/ethyl acetate = 20/1) to give the product (**2.32a**) (118.4 mg, 84%). The NMR spectrum is consistent with previously reported data.[3]

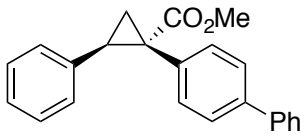
^{1}H NMR (400 MHz, $CDCl_3$): δ 7.09-7.06 (m, 3H), 6.95-6.92 (m, 2H), 6.78-6.76 (m, 2H), 6.68-6.65 (m, 2H), 3.72 (s, 3H), 3.67 (s, 3H), 3.07 (dd, *J* = 9.6, 7.6 Hz, 1H), 2.13 (dd, *J* = 9.6, 5.2 Hz, 1H), 1.83 (dd, *J* = 7.6, 5.2 Hz, 1H); HPLC: (Chiralcel OD, 0.7% isopropanol in hexane, 1mL/min, 1 mg/mL, 30 min, UV 254 nm) retention times of 13.7 min (major) and 20.1 min (minor), 57% ee.



[3] Davies, H. M. L.; Venkataramani, C. *Org. Lett.* **2003**, *5*, 1403.

(1*S*,2*R*)-methyl 1-(2-methoxyphenyl)-2-phenylcyclopropanecarboxylate (**2.32b**)

Prepared according to the general procedure for Rh(II)-catalyzed cyclopropanation of alkenes using methyl 2-diazo-2-(2-methoxyphenyl)acetate (**2.31b**) (90 mg, 0.5 mmol, 1.0 equiv) and styrene (**2.2**) (260 mg, 2.5 mmol, 5.0 equiv) with Rh_2(*R*-BNP)$_4$ (8.0 mg, 1 mol%) at room temperature, and purified by flash column chromatography (hexanes/ethyl acetate = 20/1) to give the product (**2.32b**) as a sticky oil (97.3 mg, 69%). $[\alpha]^{20}_{D:}$ 53.7° (*c* = 1.82, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.19-7.10 (m, 2H), 7.04-6.98 (m, 3H), 6.83 (t, *J* = 7.6 Hz, 1H), 6.81-6.74 (m, 2H), 6.53 (d, *J* = 8.0 Hz, 1H), 3.65 (s, 3H), 3.37 (s, 3H), 3.24 (dd, *J* = 9.6, 7.6 Hz, 1H), 1.98 (dd, *J* = 9.2, 4.8 Hz, 1H), 1.85 (dd, *J* = 7.2, 4.8 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 174.7, 159.2, 137.0, 131.8, 128.9, 127.9, 127.2, 126.1, 124.1, 120.1 110.5, 55.2, 52.7, 34.3, 32.6, 20.8; IR (film): 3030, 2950, 1716, 1496, 1434, 1258, 1161, 754, 696; HRMS (ESI) calcd for $C_{18}H_{19}O_3$ $(M+H)^+$ 283.13341 found 283.13283; HPLC: (R,R-Whelk, 1% isopropanol in hexane, 1mL/min, 1 mg/mL, 50 min, UV 254 nm) retention times of 12.1 min (major) and 13.6 min (minor), 27% ee.

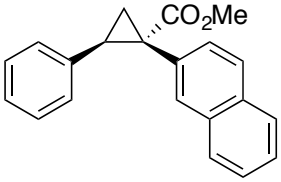


(1*S*,2*R*)-methyl 1-([1,1'-biphenyl]-4-yl)-2-phenylcyclopropanecarboxylate (**2.32c**)

Prepared according to the general procedure for Rh(II)-catalyzed cyclopropanation of alkenes using methyl 2-([1,1'-biphenyl]-4-yl)-2-diazoacetate (**2.31c**) (126 mg, 0.5 mmol, 1.0 equiv) and styrene (**2.2**) (260 mg, 2.5 mmol, 5.0 equiv) with Rh_2(*R*-BNP)$_4$ (8.0 mg, 1 mol%) at room temperature, and purified by flash column chromatography

(hexanes/ethyl acetate = 20/1) to give the product (**2.32c**) as a white solid (132.8 mg, 81%).

Mp: 157-158 ^{o}C; [α] $^{20}_{D:}$ -17.7 (*c* = 1.05, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.56 (d, *J* = 8.4 Hz, 2H), 7.44-7.39 (m, 4H), 7.33 (t, *J* = 7.2 Hz, 1H), 7.14-7.07 (m, 5H), 6.86-6.82 (m, 2H), 3.72 (s, 3H), 3.17 (dd, *J* = 9.2, 7.2 Hz, 1H), 2.21 (dd, *J* = 9.6, 5.2 Hz, 1H), 1.94 (dd, *J* = 7.2, 4.8 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 174.5, 140.8, 139.8, 136,5, 134.0, 132.5, 128.8, 128.3, 128.0, 127.4, 127.1, 126.54, 126.52, 52.9, 37.3, 33.5, 20.8; IR (film): 3029, 2950, 1716, 1488, 1254; HRMS (ESI) calcd for $C_{23}H_{21}O_2$ $(M+H)^+$ 329.15415 found 329.15348; HPLC: (R,R-Whelk, 2% isopropanol in hexane, 1mL/min, 1 mg/mL, 50 min, UV 254 nm) retention times of 16.2 min (minor) and 23.7 min (major), 59% ee.

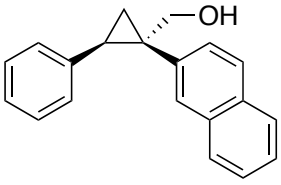


(1*S*,2*R*)-methyl 1-(naphthalen-2-yl)-2-phenylcyclopropanecarboxylate (**2.32d**)

Prepared according to the general procedure for Rh(II)-catalyzed cyclopropanation of alkenes using methyl 2-diazo-2-(naphthalen-2-yl)acetate (**2.31d**) (113 mg, 0.5 mmol, 1.0 equiv) and styrene (**2.2**) (260 mg, 2.5 mmol, 5.0 equiv) with Rh_2(*R*-BNP)$_4$ (8.0 mg, 1 mol%) at room temperature, and purified by flash column chromatography (hexanes/ethyl acetate = 20/1) to give the product (**2.32d**) as a clear oil (141.2 mg, 94%).

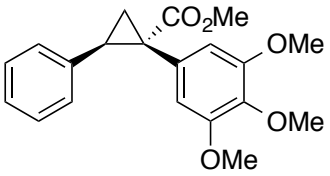
^{1}H NMR (400 MHz, $CDCl_3$): δ 7.72 (dd, *J* = 9.6, 5.2 Hz, 2H), 7.61 (s, 1H), 7.53 (d, *J* = 8.4 Hz, 1H), 7.04 (dd, *J* = 8.8, 1.6 Hz, 1H), 7.02-6.99 (m, 3H), 6.83-6.80 (m, 2H), 3.66

(s, 3H), 3.20 (dd, *J* = 9.2, 4.8 Hz, 1H), 2.23 (dd, *J* = 9.2, 4.8 Hz, 1H), 2.03 (dd, *J* = 7.2, 4.8 Hz, 1H). The NMR spectrum is consistent with previously reported data.[4] The enantioselectivity was determined by the alcohol **2.32d**-alcohol derived from DIBAL reduction of corresponding ester **2.32d**, please see below:



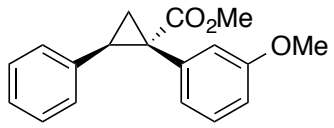
((1*S*,2*R*)-1-(naphthalen-2-yl)-2-phenylcyclopropyl)methanol (**2.32d**-alcohol)

White solid; mp: 102-103 ^{o}C; [α] $^{20}_{D:}$ -77.4^{o} (*c* = 5.17, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.75-7.73 (m, 2H), 7.68 (s, 1H), 7.61 (d, *J* = 8.4 Hz, 1H), 7.44-7.41 (m, 2H), 7.14 (dd, *J* = 8.8, 1.6 Hz, 1H), 7.03-6.97 (m, 3H), 6.81-6.78 (m, 2H), 4.99 (dd, *J* = 11.2, 5.2 Hz, 1H), 3.66 (dd, *J* = 11.2, 6.8 Hz, 1H), 2.50 (dd, *J* = 8.8, 6.0 Hz, 1H), 1.64 (t, *J* = 5.2 Hz, 1H), 1.55-1.52 (m, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 138.4, 135.6, 133.2, 132.4, 130.1, 128.8, 127.8, 127.6, 127.5, 125.8, 125.7, 125.5, 100.6, 71.9, 37.9, 27.4, 16.8; IR (film): 3359, 3055, 1600, 1500, 1071, 745, 697; HRMS (ESI) calcd for $C_{20}H_{17}$ $(M+H-H_2O)^+$ 257.13283 found 257.13241; HPLC: (S,S-Whelk, 9% isopropanol in hexane, 1.0 mL/min, 1 mg/mL, 30 min, UV 254 nm) retention times of 16.5 min (major) and 18.5 min (minor), 59% ee.



(1*S*,2*R*)-methyl 2-phenyl-1-(3,4,5-trimethoxyphenyl)cyclopropanecarboxylate (**2.32e**)

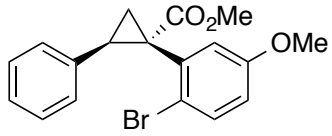
Prepared according to the general procedure for Rh(II)-catalyzed cyclopropanation of alkenes using methyl 2-diazo-2-(3,4,5-trimethoxyphenyl)acetate (**2.31e**) (133 mg, 0.5 mmol, 1.0 equiv) and styrene (**2.2**) (260 mg, 2.5 mmol, 5.0 equiv) with Rh_2(*R*-BNP)$_4$ (8.0 mg, 1 mol%) at room temperature, and purified by flash column chromatography (hexanes/ethyl acetate = 20/1) to give product (**2.32e**) as a sticky oil (107.7 mg, 63%). [α] $^{20}_{D:}$ +17.5^{o} (*c* = 2.02, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.09-7.07 (m, 3H), 6.81-6.78 (m, 2H), 6.16 (s, 2H), 3.76 (s, 3H), 3.69 (s, 3H), 3.59 (s, 3H), 3.07 (dd, *J* = 9.2, 7.2 Hz, 1H), 2.14 (dd, *J* = 9.6, 4.8 Hz, 1H), 1.82 (dd, *J* = 7.6, 5.2 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 174.2, 152.3, 136.5, 130.3, 127.9, 127.7, 126.4, 109.4, 60.7, 55.9, 52.6, 37.4, 33.1, 20.8; IR (film): 2925, 1716, 1587, 1413, 1258, 1235, 1153, 1124; HRMS (ESI) calcd for $C_{20}H_{23}O_5$ $(M+H)^+$ 343.15454 found 343.15386; HPLC: (Chiralcel OD-H, 6% isopropanol in hexane, 1 mL/min, 1 mg/mL, 30 min, UV 254 nm) retention times of 10.9 min (minor) and 11.7 min (major), 90% ee.



(1*S*,2*R*)-methyl 1-(3-methoxyphenyl)-2-phenylcyclopropanecarboxylate (**2.32f**)

Prepared according to the general procedure for Rh(II)-catalyzed cyclopropanation of alkenes using methyl 2-diazo-2-(3-methoxyphenyl)acetate (**2.31f**) (90 mg, 0.5 mmol, 1.0 equiv) and styrene (**2.2**) (260 mg, 2.5 mmol, 5.0 equiv) with Rh_2(*R*-BNP)$_4$ (8.0 mg, 1 mol %) at room temperature, and purified by flash column chromatography (hexanes/ethyl acetate = 20/1) to give the product (**2.32f**) as a clear oil (115.7 mg, 82% yield).

[α] $^{20}_{D:}$ +21.1° (*c* = 1.25, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.09-7.03 (m, 4H), 6.81-6.79 (m, 2H), 6.69-6.63 (m, 2H), 6.53-6.52 (m, 1H), 3.67 (s, 3H), 3.59 (s, 3H), 3.12 (dd, *J* = 9.6, 7.2 Hz, 1H), 2.12 (dd, *J* = 9.2, 4.8 Hz, 1H), 1.87 (dd, *J* = 7.6, 5.2 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 174.2, 158.8, 136.4, 136.2, 128.5, 127.9, 127.7, 126.3, 124.4, 117.5, 112.9, 55.0, 52.6, 37.3, 33.1, 20.6; IR (film): 2925, 1717, 1602, 1454, 1239, 697; HRMS (ESI) calcd for $C_{18}H_{19}O_3$ $(M+H)^+$ 283.13344 found 283.13288; HPLC: (Chiralcel OD-H, 0.7% isopropanol in hexane, 1 mL/min, 1 mg/mL, 30 min, UV 254 nm) retention times of 9.5 min (major) and 11.6 min (minor), 88% ee.

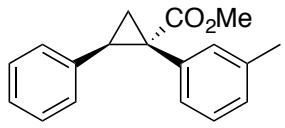


(1*S*,2*R*)-methyl 1-(4-bromo-3-methoxyphenyl)-2-phenylcyclopropanecarboxylate (**2.32g**)

Prepared according to the general procedure for Rh(II)-catalyzed cyclopropanation of alkenes using methyl 2-(2-bromo-5-methoxyphenyl)-2-diazoacetate (**2.31g**) (142 mg, 0.5 mmol, 1.0 equiv) and styrene (**2.2**) (260 mg, 2.5 mmol, 5.0 equiv) with Rh_2(*R*-BNP)$_4$ (8.0 mg, 1 mol%) at room temperature, and purified by flash chromatography (hexanes/ethyl acetate = 20/1) to give the product (**2.32g**) as a clear oil (79.2 mg, 44%).

^{1}H NMR (400 MHz, $CDCl_3$): δ 7.23-7.15 (m, 2H), 7.08-6.98 (m, 3H), 6.88 (d, *J* = 5.2 Hz, 1H), 6.62-6.60 (m, 1H), 3.80 (s, 3H), 3.67 (s, 3H), 2.02-1.99 (m, 1H), 1.91-1.89 (m, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 173.4, 136.0, 133.4, 128.4, 127.8, 126.7, 119.1, 118.7, 112.1; IR (film): 2949, 2836, 1721, 1207; HRMS (APCI) calcd for $C_{18}H_{17}O_3Br$ $(M+H)^+$ 361.04393 found 361.04327; HPLC: (ODH, 0.5% isopropanol in hexane, 1.0 mL/min, 1

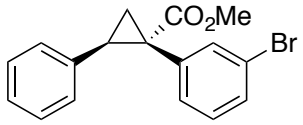
mg/mL, 30 min, UV 254 nm) retention times of 11.1 min (major) and 22.2 min (minor), 82% ee.



(1*S*,2*R*)-methyl 2-phenyl-1-(m-tolyl)cyclopropanecarboxylate (**2.32h**)

Prepared according to the general procedure for Rh(II)-catalyzed cyclopropanation of alkenes using methyl 2-diazo-2-(*m*-tolyl)acetate (**2.31h**) (80 mg, 0.5 mmol, 1.0 equiv) and styrene (**2.2**) (260 mg, 2.5 mmol, 5.0 equiv) with Rh_2(*R*-BNP)$_4$ (8.0 mg, 1 mol%) at room temperature, and purified by flash column chromatography (hexanes/ethyl acetate = 20/1) to give the product (**2.32h**) as a clear oil (67.8 mg, 51%).

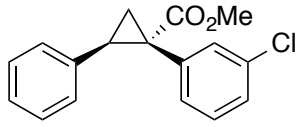
$[\alpha]^{20}_{D:}$ +9.78^{o} (*c* = 1.25, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.07-7.05 (m, 3H), 7.10-6.98 (m, 1H), 6.95-6.94 (m, 1H), 6.85 (s, 1H), 6.80-6.76 (m, 3H), 3.67 (s, 3H), 3.10 (dd, *J* = 9.2, 7.2 Hz, 1H), 2.19 (s, 3H), 2.12 (dd, *J* = 9.2, 5.2 Hz, 1H), 1.85 (dd, *J* = 7.2, 4.8 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 174.5, 137.1, 136.5, 134.5, 132.6, 129.0, 128.0, 127.8, 127.6, 127.4, 126.2, 52.6, 37.2, 33.1, 21.2, 20.6; IR (film): 2925, 1716, 1257, 1157, 702; HRMS (ESI) calcd for $C_{18}H_{19}O_2$ $(M+H)^+$ 267.13850 found 267.13790; HPLC: (S,S-Whelk, 1.5% isopropanol in hexane, 0.7mL/min, 1 mg/mL, 30 min, UV 254 nm) retention times of 11.9 min (major) and 13.9 min (minor), 42% ee.



(1*S*,2*R*)-methyl 1-(3-bromophenyl)-2-phenylcyclopropanecarboxylate (**2.32i**)

Prepared according to the general procedure for Rh(II)-catalyzed cyclopropanation of alkenes using methyl 2-(3-bromophenyl)-2-diazoacetate (**2.31i**) (127 mg, 0.5 mmol, 1.0 equiv) and styrene (**2.2**) (260 mg, 2.5 mmol, 5.0 equiv) with Rh_2(*R*-BNP)$_4$ (8.0 mg, 1 mol %) at room temperature, and purified by flash column chromatography (hexanes/ethyl acetate = 20/1) to give the product (**2.32i**) as a clear oil (115.5 mg, 70%).

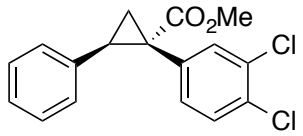
$[\alpha]^{20}_{D:}$ -6.2 (*c* = 1.31, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.21-7.15 (m, 2H), 7.03-7.02 (m, 3H), 6.92-6.88 (t, *J* = 7.6 Hz, 1H), 6.84-6.81 (m, 1H), 6.74-6.71 (m, 1H), 3.61 (s, 3H), 3.06 (dd, *J* = 9.6, 7.6 Hz, 1H), 2.07 (dd, *J* = 9.2, 5.2 Hz, 1H), 1.81 (dd, *J* = 7.2, 4.8 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 173.7, 137.2, 135.7, 134.8, 130.7, 130.2, 129.1, 127.9, 127.8, 126.6, 121.5, 52.7, 36.9, 33.2, 20.2; IR (film): 2925, 1717, 1432, 1267, 1252, 1210; HRMS (ESI) calcd for $C_{17}H_{16}O_2Br$ $(M+H)^+$ 331.03336 found 331.03273; HPLC: (S,S-Whelk, 1.5% isopropanol in hexane, 0.7mL/min, 1 mg/mL, 30 min, UV 254 nm) retention times of 13.3 min (major) and 16.2 min (minor), 70% ee.



(1*S*,2*R*)-methyl 1-(3-chlorophenyl)-2-phenylcyclopropanecarboxylate (**2.32j**)

Prepared according to the general procedure for Rh(II)-catalyzed cyclopropanation of alkenes using methyl 2-(3-chlorophenyl)-2-diazoacetate (**2.31j**) (105 mg, 0.5 mmol, 1.0 equiv) and styrene (**2.2**) (260 mg, 2.5 mmol, 5.0 equiv) with Rh_2(*R*-BNP)$_4$ (8.0 mg, 1 mol%) at room temperature, and purified by flash column chromatography (hexanes/ethyl acetate = 20/1) to give the product (**2.32j**) as a sticky oil (95.8 mg, 67%).

$[\alpha]^{20}_{D:}$ +2.17° (*c* = 2.03, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.11-7.01 (m, 6H), 7.01-6.78 (m, 3H), 3.67 (s, 3H), 3.13 (dd, *J* = 9.6, 7.6 Hz, 1H), 2.15 (dd, *J* = 10.4, 5.6 Hz, 1H), 1.87 (dd, *J* = 7.6, 4.8 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 173.6, 136.9, 135.7, 133.4, 131.9, 130.2, 128.8, 127.9, 127.8, 127.2, 126.6, 52.7, 36.9, 33.2, 20.2; IR (film): 2925, 1717, 1433, 1268, 1252, 1210, 1161, 692; HRMS (ESI) calcd for $C_{17}H_{14}O_2Cl$ $(M-H)^+$ 285.06824 found 285.06879; HPLC: (OJ-H, 1% isopropanol in hexane, 1 mL/min, 1 mg/mL, 30 min, UV 254 nm) retention times of 12.2 min (minor) and 13.5 min (major), 50% ee.

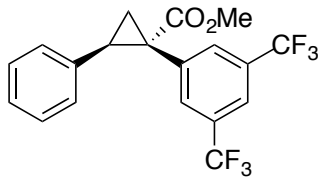


(1*S*,2*R*)-methyl 1-(3,4-dichlorophenyl)-2-phenylcyclopropanecarboxylate (**2.32k**)

Prepared according to the general procedure for Rh(II)-catalyzed cyclopropanation of alkenes using methyl 2-diazo-2-(3,4-dichlorophenyl)acetate (**2.31k**) (122 mg, 0.5 mmol, 1.0 equiv) and styrene (**2.2**) (260 mg, 2.5 mmol, 5.0 equiv) with Rh_2(*R*-BNP)$_4$ (8.0 mg, 1 mol%) at room temperature, and purified by flash column chromatography (hexanes/ethyl acetate = 20/1) to give the product (**2.32k**) as a clear oil (131.2 mg, 82%).

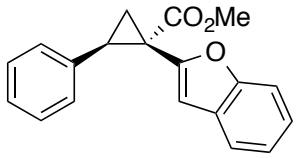
$[\alpha]^{20}_{D:}$ –8.1° (*c* = 1.60, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.18-7.16 (m, 2H), 7.14-7.10 (m, 3H), 6.82-6.79 (m, 3H), 3.68 (s, 3H), 3.14 (dd, *J* = 9.2, 7.6 Hz, 1H), 2.15 (dd, *J* = 9.2, 4.8 Hz, 1H), 1.84 (dd, *J* = 7.6, 5.2 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 173.3, 135.3, 135.2, 133.7, 131.6, 131.4, 131.2, 129.6, 128.0, 127.9, 126.8, 52.8, 36.3, 33.3, 20.2; IR (film): 2925, 1719, 1257, 1163, 695; HRMS (ESI) calcd for $C_{17}H_{13}O_2Cl_2$ $(M-H)^+$ 319.02927 found 319.02985; HPLC: (Chiralcel OD-H, 1% isopropanol in hexane, 1

mL/min, 1 mg/mL, 30 min, UV 254 nm) retention times of 7.6 min (minor) and 9.8 min (major), 63% ee.



(1*S*,2*R*)-methyl 1-(3,5-bis(trifluoromethyl)phenyl)-2-phenylcyclopropanecarboxylate (**2.32l**)

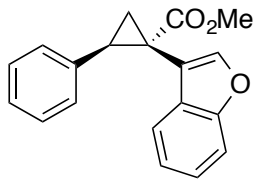
Prepared according to the general procedure for Rh(II)-catalyzed cyclopropanation of alkenes using methyl 2-(3,5-bis(trifluoromethyl)phenyl)-2-diazoacetate (**2.31l**) (156 mg, 0.5 mmol, 1.0 equiv) and styrene (**2.2**) (260 mg, 2.5 mmol, 5.0 equiv) with Rh_2(*R*-BNP)$_4$ (8.0 mg, 1 mol%) at room temperature, and purified by flash column chromatography (hexanes/ethyl acetate = 20/1) to give the product (**2.31l**) as a clear oil (110.6 mg, 57%). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.63 (s, 1H), 7.44 (s, 1H), 7.12-7.09 (m, 3H), 6.80 (dd, *J* = 6.9, 2.6 Hz, 2H), 3.25 (dd, *J* = 9.3, 7.5 Hz, 1H), 2.27 (dd, *J* = 9.3, 5.3 Hz, 1H), 1.97 (dd, *J* = 7.5, 5.3 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 172.7, 137.8, 134.7, 132.1, 131.3, 131.0, 130.7, 130.3, 128.2, 127.8, 127.1, 124.4, 121.7, 120.9, 119.0, 52.8, 36.5, 33.3, 19.6; ^{19}F NMR (376 MHz, $CDCl_3$) δ -63.4; IR (film): 2957, 1723, 1274, 1126; HRMS (APCI) calcd for $C_{19}H_{1f}O_2F_6$ $(M+H)^+$ 389.09762 found 389.09712; HPLC: (ODH, 0.5% isopropanol in hexane, 1.0 mL/min, 1 mg/mL, 30 min, UV 254 nm) retention times of 4.6 min (minor) and 5.7 min (major), 37% ee.



(1*S*,2*R*)-methyl 1-(benzofuran-2-yl)-2-phenylcyclopropanecarboxylate (**2.32m**)

Prepared according to the general procedure for Rh(II)-catalyzed cyclopropanation of alkenes using methyl 2-(benzofuran-2-yl)-2-diazoacetate (**2.31m**) (108 mg, 0.5 mmol, 1.0 equiv) and styrene (**2.2**) (260 mg, 2.5 mmol, 5.0 equiv) with Rh_2(*R*-BNP)$_4$ (8.0 mg, 1 mol%) at room temperature, and purified by flash column chromatography (hexanes/ethyl acetate = 20/1) to give the product (**2.32m**) as a yellow solid (97.8 mg, 67%).

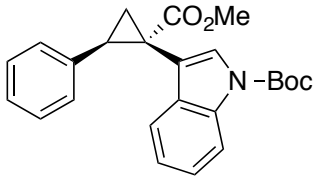
Mp: 99-100 ^{o}C; [α] $^{20}_{D:}$ +34.5^{o} (*c* = 1.90, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.34-7.32 (m, 1H), 7.24-7.19 (m, 1H), 7.12-6.97 (m, 7H), 6.27 (d, *J* = 0.8 Hz, 1H), 3.67 (s, 3H), 3.21 (t, *J* = 8.8 Hz, 1H), 2.13-2.05 (m, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 172.4, 154.6, 152.2, 135.3, 128.1, 127.9, 127.8, 126.9, 123.8, 122.3, 120.7, 110.8, 107.6, 52.8, 34.1, 30.9, 20.6; IR (film): 2925, 1722, 1453, 1268, 1256, 1157; HRMS (ESI) calcd for $C_{19}H_{17}O_3$ $(M+H)^+$ 293.11776 found 293.11715; HPLC: (S,S-Whelk, 1.5% isopropanol in hexane, 0.7mL/min, 1 mg/mL, 30 min, UV 254 nm) retention times of 18.8 min (major) and 23.6 min (minor), 70% ee.



(1*S*,2*R*)-methyl 1-(benzofuran-3-yl)-2-phenylcyclopropanecarboxylate (**2.32n**)

Prepared according to the general procedure for Rh(II)-catalyzed cyclopropanation of alkenes using methyl 2-(benzofuran-3-yl)-2-diazoacetate (**2.31n**) (108 mg, 0.5 mmol, 1.0 equiv) and styrene (**2.2**) (260 mg, 2.5 mmol, 5.0 equiv) with Rh_2(*R*-BNP)$_4$ (8.0 mg, 1 mol %) at room temperature, and purified by flash column chromatography (hexanes/ethyl acetate = 20/1) to give the product (**2.32n**) as a clear oil (102.2 mg, 70%).

^{1}H NMR (400 MHz, $CDCl_3$): δ 7.40-7.34 (m, 2H), 7.22-7.18 (m, 1H), 7.15-7.13 (m, 1H), 7.07-7.04 (m, 4H), 6.99-6.97 (m, 2H), 3.68 (s, 3H), 3.24 (dd, *J* = 9.3, 7.5 Hz, 1H), 2.22-2.18 (m, 1H), 1.89 (dd, *J* = 7.5, 4.7 Hz, 1H); HPLC: (S,S-Whelk, 1.5% isopropanol in hexane, 0.7mL/min, 1 mg/mL, 30 min, UV 254 nm) retention times of 16.9 min (major) and 19.2 min (minor), 68% ee. The NMR spectrum is consistent with previously reported data.[4]



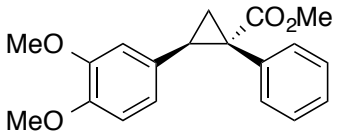
tert-butyl 3-((1*S*,2*R*)-1-(methoxycarbonyl)-2-phenylcyclopropyl)-1H-indole-1-carboxylate (**2.32o**)

Prepared according to the general procedure for Rh(II)-catalyzed cyclopropanation of alkenes using *tert*-butyl 3-(1-diazo-2-methoxy-2-oxoethyl)-1H-indole-1-carboxylate (**2.31o**) (157.5 mg, 0.5 mmol, 1.0 equiv) and styrene (**2.2**) (260 mg, 2.5 mmol, 5.0 equiv) with Rh_2(*R*-BNP)$_4$ (8.0 mg, 1 mol%) at room temperature, and purified by flash column

[4] Davies, H. M. L.; Townsend, R. J. *J. Org. Chem.* **2001**, *66*, 6595.

chromatography (hexanes/ethyl acetate = 20/1) to give the product (**2.32o**) as a sticky oil (162.2 mg, 83%).

^{1}H NMR (400 MHz, $CDCl_3$): δ 8.0 (br m, 1H), 7.32 (d, *J* = 10.0, 1H), 7.20 (t, *J* = 9.5 Hz, 1H), 7.12-7.05 (m, 4H), 6.99-6.95 (m, 3H), 3.66 (s, 3H), 3.23 (dd, *J* = 12.0 and 9.0 Hz, 1H), 2.18 (dd, *J* = 9.0 and 6.0 Hz, 1H), 1.87 (dd, *J* =9.0 and 6.0 Hz, 1H); HPLC: (Chiralcel OD-H, 1% isopropanol in hexane, 1.0 mL/min, 1 mg/mL, 30 min) retention times of 6.7 min (major) and 8.9min (minor), 84% ee. The NMR spectrum is consistent with previously reported data.[5]

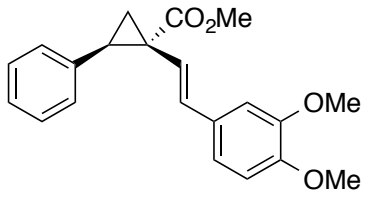


(1*S*,2*R*)-methyl 2-(3,4-dimethoxyphenyl)-1-phenylcyclopropanecarboxylate (**2.34**)

Prepared according to the general procedure for Rh(II)-catalyzed cyclopropanation of alkenes using methyl 2-diazo-2-phenylacetate (**2.1**) (88 mg, 0.5 mmol, 1.0 equiv) and 1,2-dimethoxy-4-vinylbenzene (**2.33**) (410 mg, 2.5 mmol, 5.0 equiv) with Rh_2(*R*-BNP)$_4$ (8.0 mg, 1 mol%) at room temperature, and purified by flash column chromatography (hexanes/ethyl acetate = 20/1) to give the product (**2.34**) as a colorless oil (126.4 mg, 81%).

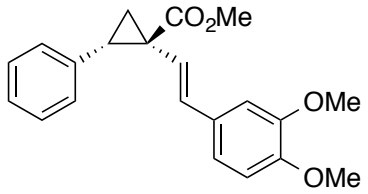
^{1}H NMR (400 MHz, $CDCl_3$): δ 7.18−7.15 (m, 2H), 7.07-7.05 (m, 2H), 6.61 (d, *J* = 8.2 Hz, 1H), 6.48 (dd, *J* = 8.2, 1.8 Hz, 1H), 6.04 (d, *J* = 1.8 Hz, 1H), 3.77 (s, 3H), 3.67 (s, 3H), 3.53 (s, 3H), 3.05 (dd, *J* = 9.5, 7.3 Hz, 1H), 2.15 (dd, *J* = 9.5, 4.9 Hz, 1H), 1.79 (dd, *J* = 7.2, 5.0 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 174.3, 148.1, 147.5, 134.9, 131.9, 128.9, 127.8, 126.9, 120.6, 110.7, 110.4, 55.7, 55.5, 52.6, 37.1, 32.9; IR (film): 2951,

2835, 1714, 1518, 1464, 1252; HRMS (APCI) calcd for $C_{19}H_{20}O_4$ $(M+H)^+$ 313.14398 found 313.14340. HPLC: (ODH, 6% isopropanol in hexane, 1.0 mL/min, 1 mg/mL, 30 min, UV 254 nm) retention times of 12.5 min (major) and 13.8 min (minor), 46% ee.



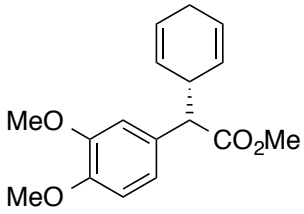
(1*R*,2*R*)-methyl 1-((*E*)-3,4-dimethoxystyryl)-2-phenylcyclopropanecarboxylate (**2.36**)

Prepared according to the general procedure for Rh(II)-catalyzed cyclopropanation of alkenes using methyl (*E*)-2-diazo-4-(3,4-dimethoxyphenyl)but-3-enoate (**2.35**) (131 mg, 0.5 mmol, 1.0 equiv) and styrene (**2.2**) (410 mg, 2.5 mmol, 5.0 equiv) with Rh_2(*R*-BNP)$_4$ (8.0 mg, 1 mol%) at room temperature, and purified by flash column chromatography (hexanes/ethyl acetate = 20/1) to give the product (**2.36**) as a yellow oil (121.7 mg, 72%). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.25-7.21 (m, 2H), 7.19-7.13 (m, 3H), 6.75-6.65 (m, 3H), 6.31 (d, *J* = 15.9 Hz, 1H), 5.97 (d, *J* = 15.9 Hz, 1H), 3.85(s, 3H), 3.81 (s, 3H), 3.77 (s, 3H), 3.01-2.98 (m, 1H), 2.02 (dd, *J* = 9.0, 5.0 Hz, 1H), 1.82 (dd, *J* = 7.3, 5.2Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 174.2, 148.8, 148.6, 135.6, 132.9, 130.2, 129.0, 127.9, 126.6, 122.2, 119.2, 110/9, 108.8, 55.8, 55.7, 52.4, 34.7, 33.2, 18.6; IR (film): 2950, 1716, 1512, 1453, 1246; HRMS (APCI) calcd for $C_{21}H_{22}O_4$ $(M+Na)^+$ 361.14158 found 361.14133. HPLC: (ODH, 6% isopropanol in hexane, 1.0 mL/min, 1 mg/mL, 30 min, UV 254 nm) retention times of 12.3 min (minor) and 13.4 min (major), 61% ee.



(1*S*,2*S*)-methyl 1-((*E*)-3,4-dimethoxystyryl)-2-phenylcyclopropanecarboxylate (***S*-2.36**)

Prepared according to general procedure for Rh(II)-catalyzed cyclopropanation of alkenes using methyl (*E*)-2-diazo-4-(3,4-dimethoxyphenyl)but-3-enoate (**2.35**) (26.2 mg, 0.1 mmol, 1.0 equiv) and styrene (**2.2**) (82 mg, 0.5 mmol, 5.0 equiv) with Rh_2(*S*-CBNP)$_4$ (1.6 mg, 1 mol%) at room temperature, and purified by flash column chromatography (hexanes/ethyl acetate = 20/1) to give product (***S*-2.36)** (17.2 mg, 51%). HPLC: (ODH, 6% isopropanol in hexane, 1.0 mL/min, 1 mg/mL, 30 min, UV 254 nm) retention times of 12.3 min (minor) and 13.4 min (major), 51% ee.

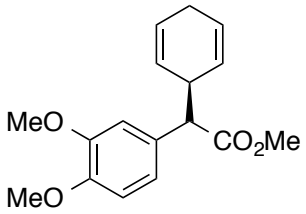


(*R*)-methyl 2-(cyclohexa-2,5-dien-1-yl)-2-(3,4-dimethoxyphenyl)acetate (**2.38**)

Prepared according to the general procedure for Rh(II)-catalyzed C–H insertion reaction using methyl 2-diazo-2-(3,4-dimethoxyphenyl)acetate (**2.29**) (118 mg, 0.5 mmol, 1.0 equiv) and cyclohexa-1,4-diene (**2.37**) (200 mg, 2.5 mmol, 5.0 equiv) with Rh_2(*R*-BNP)$_4$ (8.0 mg, 1 mol%) at room temperature, and purified by flash column chromatography (hexanes/ethyl acetate = 20/1) to give the product (**2.38**) as a clear oil (84.9 mg, 59%).

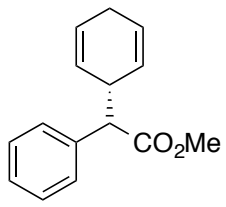
$[\alpha]_{D}^{20}$ +53.4 (*c* = 2.10, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$): δ 6.89-6.79 (m, 3H), 5.82-5.78 (m, 1H), 5.71-5.67 (m, 2H), 5.30-5.26 (m, 1H), 3.87 (s, 3H), 3.86 (s, 3H), 3.673.49-

3.40 (m, 1H), 3.34 (d, J = 10.8 Hz, 1H), 2.64-2.60 (m, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 173.9, 149.2, 148.6, 129.5, 126.9, 126.5, 126.2, 126.0, 121.2, 111.6, 111.4, 111.3, 58.1, 56.2, 56.1, 52.2, 38.9, 29.9, 26.7; IR (film): 2924, 2853, 1731, 1514, 1188, 1152, 1026, 702; HRMS (ESI) calc for $C_{17}H_{21}O_4$ $(M+H)^+$ 289.14398 found 289.14337; HPLC: (Chiralcel OD, 0.4% isopropanol in hexane, 0.9 mL/min, 1 mg/mL, 60 min) retention times of 44.8 min (major) and 66.2 min (minor), 78% ee.



(*S*)-methyl 2-(cyclohexa-2,5-dien-1-yl)-2-(3,4-dimethoxyphenyl)acetate (***S*-2.38**)

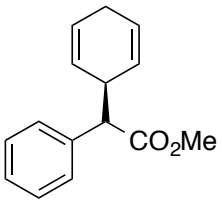
Prepared according to the general procedure for Rh(II)-catalyzed C-H insertion reaction using methyl 2-diazo-2-(3,4-dimethoxyphenyl)acetate (**2.29**) (23.6 mg, 0.1 mmol, 1.0 equiv) and cyclohexa-1,4-diene (**2.37**) (40 mg, 0.5 mmol, 5.0 equiv) with Rh_2(*S*-CBNP)$_4$ (1.6 mg, 1 mol%) at room temperature, and purified by flash column chromatography (hexanes/ethyl acetate = 20/1) to give the product (***S*-2.38**) (12.1 mg, 42%). HPLC: (Chiralcel OD, 0.4% isopropanol in hexane, 0.9 mL/min, 1 mg/mL, 60 min) retention times of 44.8 min (major) and 66.2 min (minor), 89% ee.



(*R*)-methyl 2-(cyclohexa-2,5-dien-1-yl)-2-phenylacetate (**2.39**)

Prepared according to the general procedure for Rh(II)-catalyzed C–H insertion reaction using methyl 2-diazo-2-phenylacetate (**2.1**) (88 mg, 0.5 mmol, 1.0 equiv) and cyclohexa-1,4-diene (**2.37**) (200 mg, 2.5 mmol, 5.0 equiv) with Rh_2(*R*-BNP)$_4$ (8.0 mg, 1 mol%) at room temperature, and purified by flash column chromatography (hexanes/ethyl acetate = 20/1) to give the product (**2.39**) (107.1 mg, 94%). The NMR spectrum is consistent with previously reported data.[5]

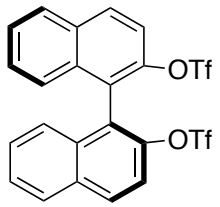
^{1}H NMR (400 MHz, $CDCl_3$): δ 7.32-7.24 (m, 5H), 5.81-5.77 (m, 1H), 5.71-5.65 (m, 2H), 5.26-5.22 (m, 1H), 3.66 (s. 1H), 3.47-3.45 (m, 1H), 3.41-3.39 (m, 1H), 2.61-2.58 (m, 2H); HPLC: (OJH, 0.5% isopropanol in hexane, 0.5 mL/min, 1 mg/mL, 30 min, UV 254 nm) retention times of 13.9 min (major) and 14.6 min (minor), 23% ee.



(*S*)-methyl 2-(cyclohexa-2,5-dien-1-yl)-2-phenylacetate (***S*-2.39**)

Prepared according to the general procedure for Rh(II)-catalyzed C–H insertion reaction using methyl 2-diazo-2-phenylacetate (**2.1**) (17.6 mg, 0.1 mmol, 1.0 equiv) and cyclohexa-1,4-diene (**2.37**) (40 mg, 0.5 mmol, 5.0 equiv) with Rh_2(*S*-CBNP)$_4$ (1.6 mg, 1 mol%) at room temperature, and purified by flash column chromatography (hexanes/ethyl acetate = 20/1) to give product (***S*-2.39**) (14.1 mg, 62%); HPLC: (OJH, 0.5% isopropanol in hexane, 0.5 mL/min, 1 mg/mL, 30 min, UV 254 nm) retention times of 13.9 min (major) and 14.6 min (minor), 42% ee.

[5] Davies, H. M. L.; Walji, A. M. *Org. Lett.* **2003**, *5*, 479.

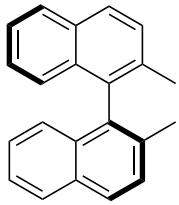


(*S*)-[1,1'-binaphthalene]-2,2'-diyl bis(trifluoromethanesulfonate) (**2.42**)

A flame-dried 250 mL flask was charged with (*S*)-[1,1'-binaphthalene]-2,2'-diol (**2.41**) (2.0 g, 7.0 mmol) in dichloromethane (50 mL). Pyridine (20 mL) was added under argon atmosphere followed by slow-addition of triflate anhydride (2.59 mL, 15.4 mol) at 0 °C. The reaction went to room temperature slowly and stirred overnight. The reaction was quenched by water and extracted by dichloromethane (3 x 50 mL). The mixture was concentrated under reduced pressure and purified by flash column chromatography in silica gel (dichloromethane) to provide the product (**2.42**) as a yellow foam (3.64 g, 95%).

^{1}H NMR (400 MHz, $CDCl_3$): δ 8.13 (d, J = 8.8 Hz, 2H), 8.0 (d, J = 8.2 Hz, 2H), 7.62-7.56 (m, 4H), 7.42-7.38 (m, 2H), 7.25-7.23 (m, 3H), 7.18 (d, J = 8.5 Hz, 2H), 4.82 (d, J = 5.8 Hz, 2H), 4.70 (d, J = 5.8 Hz, 2H), 2.60 (s, 6H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 145.3, 133.1, 132.3, 131.9, 128.3, 127.9, 127.3, 126.7, 123.4, 119.3, 118.1 (q, J = 318.7 Hz); ^{19}F NMR (376 MHz, $CDCl_3$) δ -75.0. The NMR spectrum is consistent with previously reported data.[6]

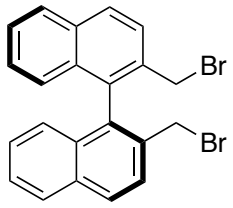
[6] Sun, X. F.; Li, W.; Zhou, L.; Zhang, X. M. *Chem. Eur. J.* **2009**, *15*, 7302.



(*S*)-2,2'-dimethyl-1,1'-binaphthalene (**2.43**)

A flame-dried 100 mL flask was charged with (*S*)-[1,1'-binaphthalene]-2,2'-diyl bis(trifluoromethanesulfonate) (**2.42**) (3.64 g, 6.62 mmol) and $NiCl_2$dppp (180 mg, 5 mol%) in dry diethyl ether (50 mL). The mixtur**e** was degassed with argon for 20 minutes at room temperature and then cooled to 0 °C. Methylmagnesium bromide (3 M in ether, 13.2 mL) was added drop-wise in one hour. After addition, the reaction was refluxed under argon overnight. The reaction was quenched by water (20 mL) and extracted by diethyl ether (3 x 100 mL). The mixture was concentrated under reduced pressure and purified by flash column chromatography (hexanes/ethyl acetate = 10/1) to provide the product (**2.43**) as a white foam (1.7 g, 91%).

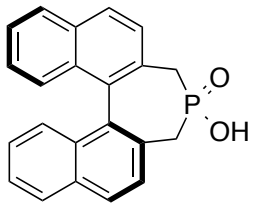
^{1}H NMR (400 MHz, $CDCl_3$): δ 7.94-7.90 (m, 4H), 7.54 (d, J = 8.2 Hz, 2H), 7.44-7.40 (m, 2H), 7.26-7.21 (m, 2H), 7.10 (d, J = 8.2 Hz, 2H), 2.08 (s, 6H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 135.1, 134.2, 132.7, 132.2, 128.7, 127.9, 127.4, 126.1, 125.6, 124.9, 20.0. The NMR spectrum is consistent with previously reported data.[6]



(*S*)-2,2'-bis(bromomethyl)-1,1'-binaphthalene (**2.44**)

A flame-dried 100 mL flask was charged with (*S*)-2,2'-dimethyl-1,1'-binaphthalene (**2.43**) (1.7 g, 6.03 mmol) and *N*-bromosuccinimide (2.25 mg, 12.7 mmol) in dry tetrachloroethane (20 mL). The mixture was degassed by bubbling with argon for 20 minutes at room temperature and then was heated to 65 °C. A solution of azobisisobutyronitrile (99 mg, 0.6 mmol, 10 mol%) in dry tetrachloroethane (10 mL) was slowly added at 65 °C. After addition, the reaction miture was heated 80 °C for 12 hours. The reaction was quenched by water (10 mL) and extracted by dichloromethane (3 x 50 mL). The mixture was concentrated under reduced pressure and purified by flash column chromatography (hexanes/ethyl acetate = 15/1) to provide the product (**2.44**) as a white powder (1.68 g, 64%).

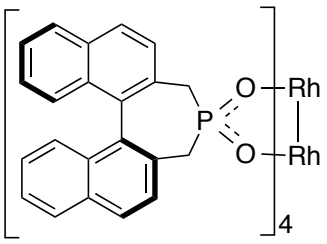
^{1}H NMR (400 MHz, $CDCl_3$): δ 8.03 (d, *J* = 8.5 Hz, 2H), 7.94 (d, *J* = 8.2 Hz, 2H), 7.76 (d, *J* = 8.5 Hz, 2H), 7.50 (t, *J* = 7.6 Hz, 2H), 7.30-7.27 (m, 2H), 7.08 (d, *J* = 8.2 Hz, 2H), 4.27 (s, 4H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 134.1, 134.0, 133.2, 132.4, 129.3, 127.9, 127.7, 126.8, 126.7, 32.6. The NMR spectrum is consistent with previously reported data.[6]



(*S*)-4-hydroxy-4,5-dihydro-3H-dinaphtho[2,1-c:1',2'-e]phosphepine 4-oxide (**2.45**)

Diisopropylethylamine (2.28 mL, 13.8 mmol) was added to a suspension of ammonium phosphinate (315.4 mg, 3.8 mmol) in dichloromethane (20 mL) at 0 °C. After the mixture was stirred for 20 minutes, chlorotrimethylsilane (1.76 mL, 13.9 mmol) was added at 0

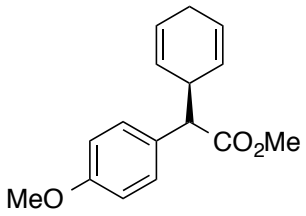
°C. The mixture was stirred for 2.0 h at room temperature, a solution of (*S*)-2,2′-di(bromomethyl)-1,1′-binaphthyl (**2.44**) (1.1 g, 2.5 mmol) in dichloromethane (5 mL) was added at 0 °C, and the mixture as stirred for additional 24 h. The reaction was carefully quenched with water (5 mL) at 0 °C, and the organic phase washed twice with aqueous HCl (10%, 5 mL) and with water (5 mL). The organic layer was dried over magnesium sulfate and concentrated and purified by flash column chromatography (CH_2Cl_2/MeOH = 95/5) to afford the product **106** as a brown pale solid (294 mg, 34%). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.93 (d, *J* = 7.9 Hz, 2H), 7.54 (d, *J* = 7.9 Hz, 4H), 7.45 (t, *J* = 7.2 Hz, 4H), 7.27-7.19 (m, 4H), 3.15-3.04 (m, 4H); ^{31}P NMR (121 MHz, $CDCl_3$) δ -66.8. The NMR spectrum is consistent with previously reported data.[6]



tetrakis[(*S*)-4-hydroxy-4,5-dihydro-3H-dinaphtho[2,1-c:1',2'-e]phosphepine 4-oxide]dirhodium catalyst, Rh_2(*S*-CBNP)$_4$ (**2.40**)

To a 50 mL flask was fitted with a Soxhlet extractor containing a 1:1 sand and Na_2CO_3, was added (11b*S*)-4-hydroxy-3,5-dihydrodinaphtho[2,1-c:1',2'-e]phosphepine 4-oxide (**2.45**) (246.2 g, 0.72 mmol, 14 equiv), $Rh_2(OAc)_4$ (22.5 g, 0.051 mmol), and 10 mL of anhydrous chlorobenzene, the reaction was refluxed at 150-160 °C for 24 h. Then, the chlorobenzene was removed and the crude residue was purified by flash column chromatography (toluene/acetonitrile = 20/1) to afford the product (**2.40**) (19.8 mg, 24%).

^{1}H NMR (400 MHz, $CDCl_3$): δ 7.92-7.87 (m, 4H), 7.43-7.36 (m, 4H), 7.15-7.05 (m, 4H), 7.27-7.23 (m, 2H), 2.85-2.78 (m, 2H), 2.70-2.61 (m, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 133.4, 133.3, 132.5, 132.4, 132.1, 131.0, 128.5, 128.0, 126.8, 125.9, 125.2, 30.9; ^{31}P NMR (121 MHz, $CDCl_3$) δ -97.1; IR (film): 3416, 3054, 2922, 1187, 995.



(*S*)-methyl 2-(cyclohexa-2,5-dien-1-yl)-2-(4-methoxyphenyl)acetate (**2.46**)

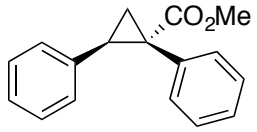
Prepared according to the general procedure for Rh(II)-catalyzed C–H insertion reaction using methyl 2-diazo-2-(4-methoxyphenyl)acetate (**2.31a**) (103 mg, 0.5 mmol, 1.0 equiv) and cyclohexa-1,4-diene (**2.37**) (200 mg, 2.5 mmol, 5.0 equiv) with Rh_2(*S*-CBNP)$_4$ (8.0 mg, 1 mol%) at room temperature, and purified by flash column chromatography (hexanes/ethyl acetate = 20/1) to give the product (**2.46**) (64.2 mg, 49%). The NMR spectrum is consistent with previously reported data.[7]

^{1}H NMR (400 MHz, $CDCl_3$): δ 7.27-7.25 (m, 3H), 6.89-6.86 (m, 2H), 5.83-5.79 (m, 1H), 5.72-5.68 (m, 1H), 5.31-5.27 (m, 1H), 3.81 (s. 3H), 3.68 (s. 3H), 3.45-3.43 (m, 1H), 3.38-3.56 (m, 1H), 2.64-2.61 (m, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 173.7, 158.9, 129.6, 128.8, 126.7, 126.2, 125.9, 125.8, 113.9, 57.4, 55.2, 51.9, 38.5, 26.4; HPLC: (S,S-Whelk, 2.0% isopropanol in hexane, 1.0 mL/min, 1 mg/mL, 40 min, UV 254 nm) retention times of 11.9 min (minor) and 15.0 min (major), 26% ee.

[7] Davies, H. M. L.; Stafford, D. G.; Hansen, T. *Org*. *Lett*. **2000**, *2*, 417.

Experimental Data for Chapter III:

Experimental sequence for the synthesis of dirhodium cyclopropane carboxylate catalysts



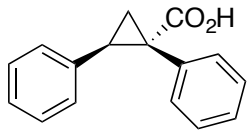
(1*S*,2*R*)-methyl 1,2-diphenylcyclopropanecarboxylate (***R*-3.13**)

To a flame-dried round bottom flask kept under a dry atmosphere of argon, was added Rh_2(*R*-DOSP)$_4$ (0.01 equiv, 379 mg), styrene (**3.8**) (2.32 equiv, 13.7 mL), and dry degassed pentane (100 mL) at room temperature. A solution of methyl 2-diazo-2-phenylacetate (**3.5**) (1.0 equiv, 3.52g) in dry, degassed pentane (100 mL), was then added to the former solution drop-wise over 3 hours under argon atmosphere. The mixture was then allowed to stir for overnight at room temperature, and concentrated *in vacuo*. The crude residue was analyzed by ^{1}H NMR and purified by flash column chromatography (hexanes/ethyl acetate = 50/1) to provide the product (***R*-3.13**) as a white solid (4.08 g, 81%). Recrystallization with a 100:1 mixture of hexane/ethyl acetate afforded the enantioenriched product (2.82g, 69% yield, >99% ee). The NMR spectrum is consistent with previously reported data.[8]

^{1}H NMR (400 MHz, $CDCl_3$): δ 7.17−7.15 (m, 3H), 7.09-7.05 (m, 5H), 6.81-6.79 (m, 2H), 3.69 (s, 3H), 3.15 (dd, *J* = 9.4, 7.3 Hz, 1H), 2.18 (dd, *J* = 9.4, 5.0 Hz, 1H), 1.92 (dd, *J* = 7.3, 5.0 Hz, 1H); HPLC (S,S-WHELK, 1.5% isopropanol in hexane, 0.7 mL/min, 1

[8] Thompson, J. L.; Davies, H. M. L. *J. Am. Chem. Soc.* **2007**, *129*, 6090.

mg/mL, 30 min, UV 254 nm) retention times of 12.9 min (major) and 15.4 min (minor), 91% ee.



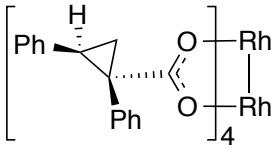
(1*S*,2*R*)-1,2-diphenylcyclopropanecarboxylic acid (***R*-3.9**)

To a round-bottom flask at ambient temperature was added enantiopure (1*S*,2*R*)-methyl 1,2-diphenylcyclopropanecarboxylate (***R*-3.13**) (11.5 mmol, 2.91g, 1.0 equiv) in dry DMSO (24 mL). The ^{t}BuOK (25.4 mmol, 2.85 g, 2.2 equiv) was added by several of portions over 30 minutes under argon. The reaction was monitored by TLC analysis until the ester was consumed completely. The reaction mixture was cooled with ice bath and was acidified by carefully adding saturated ammonium chloride (10 mL) with vigorous stirring, and then slowly adding 1 N HCl aqueous until the value of pH in the resulting solution reached to 3-4. Light yellow solids precipitated quickly and were collected by filtration. The collected solid was dissolved into ethyl acetate and washed with brine, dried over $MgSO_4$. Then, the crude residue was purified by flash column chromatography (hexanes/ethyl acetate =10/1) to afford the desired product (***R*-3.9**) as a white solid (1.64 g, 60%). The NMR spectrum is consistent with previously reported data.[9]

^{1}H NMR (400 MHz; $CDCl_3$) δ 7.15-7.14 (m, 3H), 7.08-7.03 (m, 5H), 6.79 (dd, J = 6.6, 2.9 Hz, 1H), 3.18 (dd, J = 9.3, 7.5 Hz, 1H), 2.21 (dd, J = 9.5, 4.9 Hz, 1H), 1.97 (dd, J = 7.3, 4.9 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 179.8, 136.1, 134.2, 132.1, 128.3, 127.99, 127.97, 127.5, 126.7, 37.4, 34.1, 20.9; HPLC: (note: the carboxylic acid (***R*-3.9**)

[9] Davies, H. M. L.; Walji, A. M.; Nagashima, T.; *J. Am. Chem. Soc.* **2004**, *126*, 4271.

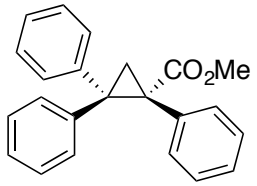
was converted to the corresponding methyl ester (***R*-3.13**) with dimethylsulfate/KOH in refluxing tetrahydrofuran for enantioselectivity test), S,S-Whelk, 1.5% isopropanol in hexane, 0.7 mL/min, 1 mg/mL, 30 min, UV 254 nm, retention times of 12.5 min (major) and 15.5 min (minor), >99% ee.



dirhodium tetrakis((1*S*,2*R*)-1,2-diphenylcyclopropanecarboxylate (***R*-3.10**)

A solution of sodium rhodium carbonate $[Na_2Rh_2(CO_3)_4]$-2.5H_2O (501 mg, 1.0 equiv) and enantiopure (1*S*,2*R*)-1,2-diphenylcyclopropanecarboxylic acid (***R*-3.9**) (1.64g, 8.0 equiv) in 35 mL distilled water was refluxed for 2 days under argon, and then the solution was extracted with dichloromethane (50mL), and washed with saturated sodium bicarbonate (3 x 10 mL), brine (3 x 10 mL), dried over anhydrous $MgSO_4$, and concentrated under vacuum. Then, the crude residue was purified by flash column chromatography (toluene/acetonitrile = from 100/1 to 50/1) to afford the desired catalyst (***R*-3.10**) (650 mg, 65%).

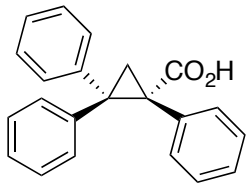
Green solid, mp: 222-224 ^oC; $[\alpha]^{20}_{D:}$ 265.1^o (*c* = 0.02, $CHCl_3$); ^1H NMR (400 MHz, $CDCl_3$): δ 7.10-7.05 (m, 24H), 6.94-6.92 (m, 8H), 6.74-6.72 (m, 8H), 2.96 (dd, *J* = 9.2, 7.3 Hz, 1H), 2.04 (dd, *J* = 9.3, 4.7 Hz, 1H), 1.77 (dd, *J* = 6.9, 5.0 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 191.6, 136.8, 135.4, 131.7, 127.9, 127.6, 127.5, 126.7, 126.1, 60.3, 39.5, 32.9, 19.7; IR (film): 3028, 1682, 1577, 1497, 1398; HRMS (ESI) calcd for $C_{64}H_{52}O_8ClRh_2$ $(M+Cl)^+$ 1189.14663 found 1189.14675.



(*R*)-methyl 1,2,2-triphenylcyclopropanecarboxylate (***R*-3.7**)

To a flame-dried round bottom flask kept under a dry atmosphere of argon, was added Rh_2(*R*-DOSP)$_4$ (0.005 equiv, 189 mg), 1,1-diphenylethlyene (**3.6**) (2.32 equiv, 8.4 g, 46.4 mmol), and dry degassed pentane (100 mL). A solution of freshly prepared methyl 2-diazo-2-phenylacetate (**3.5**) (1.0 equiv, 3.52 g, 20 mmol) in dry, degassed pentane (100 mL) was added to the former solution drop-wise over 3 hours at -78 °C, and the mixtures was allowed to stir overnight to room temperature, and then concentrated *in vacuo*. The crude material was purified using flash column chromatography (hexanes/ethyl acetate = 100/1) to provide the desired product (***R*-3.7**) as a white foam (5.4 g, 80%).

^{1}H NMR (400 MHz; $CDCl_3$) δ 7.52-7.50 (m, 2H), 7.36-7.32 (m, 4H), 7.26-7.23 (m, 1H), 7.16-7.10 (m, 3H), 6.98-6.94 (m, 5H), 3.36 (s, 3H), 2.70 (d, J = 5.5 Hz, 1H), 2.43 (d, J = 5.5 Hz, 1H); HPLC (S,S-Whelk, 9.0% isopropanol in hexane, 1.0 mL/min, 1 mg/mL, 30 min, UV 254 nm) retention times of 6.8 min (major) and 17.4 min (minor), 99% ee. The NMR spectral data is consistent with previously reported results.[10]

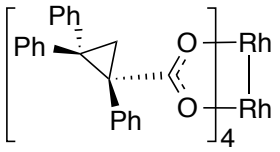


[10] Davies, H. M. L.; Nagashima, T.; Klino III, J. L. *Org. Lett.* **2000**, *8*, 5013.

(*R*)-1,2,2-triphenylcyclopropanecarboxylic acid (**3.14**)

To a round-bottom flask at room temperature was added (*R*)-methyl 1,2,2-triphenylcyclopropanecarboxylate (***R*-3.7**) (10.4 mmol, 3.4 g, 1.0 equiv) in dry DMSO (20 mL). ^{t}-BuOK (22.8 mmol, 2.6 g, 2.2 equiv) was added in several portions over 30 minutes under argon. The reaction was monitored by TLC technique until the starting material was consumed completely. The reaction mixture was cooled with ice bath and acidified by saturated ammonium chloride aqueous (15 mL), followed by a slow addition of 1 N HCl (40 mL) with vigorous stirring until the pH value reached 3-4. Sticky solid precipitate was collected by filtration, washed with water (3 x 5 mL), dissolved in ethyl acetate (150 mL), washed with brine (3 x 10 mL), dried over anhydrous $MgSO_4$, and concentrated *in vacuo*. The crude material was purified using flash column chromatography (hexanes/ethyl acetate = 4/1) to provide the desired product (***R*-3.14**) as a white solid (1.8 g, 55%).

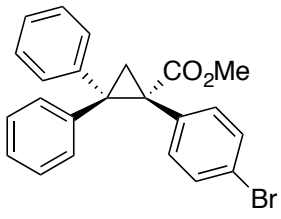
Mp: 183-185 ^{o}C; $[\alpha]^{20}_{D:}$ -223.5^{o} (*c* = 1.0, $CHCl_3$); ^{1}H NMR (400 MHz; $CDCl_3$) δ 7.46-7.44 (m, 2H), 7.29-7.24 (m, 5H), 7.12-7.08 (m, 3H), 6.95-6.91 (m, 5H), 5.72 (dt, *J* = 10.2, 2.8 Hz, 1H), 5.02-5.01 (m, 2H), 2.56-2.54 (m, 1H), 2.44-2.42 (m, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 177.2, 141.5, 139.3, 135.2, 131.8, 129.8, 128.6, 128.4, 127.5, 127.4, 127.0, 126.9, 126.1, 45.5, 42.6, 23.2; IR (film): 3025, 1686, 1495, 1449; HRMS (APCI) calcd for $C_{22}H_{17}O_2$ $(M-H)^+$ 313.12340 found 313.12320. HPLC for corresponding methyl ester (S,S-Whelk, 9.0% isopropanol in hexane, 1.0 mL/min, 1 mg/mL, 30 min, UV 254 nm) retention times of 6.8 min (major) and 17.4 min (minor), 99% ee.



dirhodium tetrakis((*R*)-1,2,2-triphenylcyclopropanecarboxylate) (**3.15**)

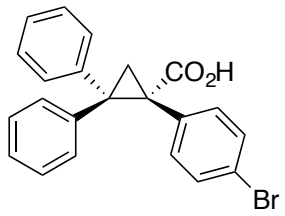
A solution of sodium rhodium carbonate $[Na_4Rh_2(CO_3)_4]$-2.5H_2O (417 mg, 0.72 mmol, 1.0 equiv) and (*R*)-1,2,2-triphenylcyclopropanecarboxylic acid (***R*-3.14**) (1.8 g, 5.73 mmol, 8.0 equiv) in distilled water (20 mL) was refluxed for 2 days under argon, and then the solution was extracted with dichloromethane (3 x 100 mL), organic extracts were combined, washed with saturated sodium bicarbonate (3 x 10 mL), 10% sodium hydroxide (3 x 10 mL), brine (3 x 10 mL), dried over anhydrous $MgSO_4$, and concentrated *in vacuo*. The crude material was purified using flash column chromatography (toluene/acetonitrile = 50/1) to provide the desired catalyst (**3.15**) as a green solid (714 mg, 68%).

Mp: 233-235 ^oC; $[\alpha]^{20}_{D:}$ -12.8^o (*c* = 0.03, $CHCl_3$); ^1H NMR (400 MHz, $CDCl_3$): δ 7.25-6.78 (m, 60H), 2.38 (d, *J* = 5.2 Hz, 4H), 1.88 (d, *J* = 5.2 Hz, 4H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 189.0, 143.0, 141.4, 136.6, 131.3, 130.2, 129.4, 128.2, 127.5, 127.4, 126.4, 126.3, 125.8, 46.5, 43.2, 23.4; IR (film): 3057, 2924, 1577, 1493, 1448, 1387; HRMS (ESI) calcd for $C_{88}H_{68}O_8ClRh_2$ $(M+Cl)^+$ 1493.27183 found 1493.27297.



(*R*)-methyl 1-(4-bromophenyl)-2,2-diphenylcyclopropanecarboxylate (**3.16**)

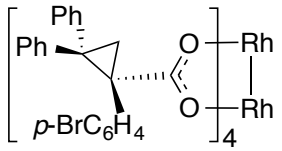
To a flame-dried round bottom flask kept under a dry atmosphere of argon, was added Rh_2(*R*-DOSP)$_4$ (0.01 equiv, 382 mg), 1,1-diphenylethlyene (**3.6**) (2.32 equiv, 8.16 mL), and dry degassed pentane (100 mL). A solution of freshly made methyl 2-(4-bromophenyl)-2-diazoacetate (**3.17**) (1.0 equiv, 5.1 g) in dry, degassed pentane (150 mL) was then added to the former solution drop-wise over 3 hours. The mixture was allowed to stir for overnight at room temperature after addition, and then concentrated *in vacuo*. The crude residue was analyzed by ^{1}H NMR and purified by flash column chromatography (hexanes/ethyl acetate = 50/1) to afford the pure (*R*)-methyl 1-(4-bromophenyl)-2,2-diphenylcyclopropanecarboxylate (**3.16)** as a white foam (7.2 g, 88%). Mp: 82-85 ^{o}C; $[\alpha]^{20}_{D:}$ -289.2 ^{o} (*c* = 1.17, $CHCl_3$); ^{1}H NMR (400 MHz; $CDCl_3$) δ 7.48-7.47 (m, 2H), 7.35-7.31 (m, 2H), 7.27-7.18 (m, 5H), 7.02-6.97 (m, 5H), 3.34 (s, 3H), 2.68 (d, *J* = 5.5 Hz, 1H), 2.39 (d, *J* = 5.9 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 170.9, 141.7, 139.1, 134.8, 133.5, 130.6, 129.8, 128.5, 128.3, 127.7, 126.9, 126.3, 121.1, 52.2, 44.6, 42.4, 22.6; IR (neat): 3057, 3024, 2947, 1724, 1490, 1217; HRMS (APCI) calcd for $C_{23}H_{20}BrO_2$ $(M+H)^+$ 407.06412 found 407.06432; HPLC: (S,S-Whelk, 5% isopropanol in hexane, 0.8 mL/min, 1 mg/mL, 60 min, UV 254 nm) retention times of 10.6 min (major) and 50.9 min (minor), 98% ee.



(*R*)-1-(4-bromophenyl)-2,2-diphenylcyclopropanecarboxylic acid (**3.17**)

To a round-bottom flask at ambient temperature was added enantiopure (*R*)-methyl 1-(4-bromophenyl)-2,2-diphenylcyclopropanecarboxylate (**3.16**) (17.9 mmol, 7.3 g, 1.0 equiv) in dry DMSO (35 mL). The ^{t}BuOK (39.6 mmol, 4.4 g, 2.2 equiv) was added by several of portions over 30 minutes under argon. The reaction was monitored by TLC analysis until the ester was consumed completely. The reaction mixture was cooled with ice bath and was initially acidified by carefully adding saturated ammonium chloride aqueous (15 mL) with vigorous stirring, and then slowly addition 1 N HCl until the pH of solution reach to around 3-4. Sticky solids precipitated quickly and were collected by filtration. The collected solid was dissolved into ethyl acetate and washed with brine (30 mL), dried over $MgSO_4$, and then purified by flash column chromatography (hexanes/ethyl acetate = 4/1) to afford the desired product (**3.17**) as a white solid (4.9 g, 69%). Recrystallization in pentane/ethyl acetate provided the enantioenriched product as a white solid (4.46 g, 64%, 99% ee). (*S*)-1-(4-bromophenyl)-2,2-diphenylcyclopropanecarboxylic acid was prepared by the same procedure, $[\alpha]^{20}_{D:}$ 260.4 ^{o} (*c* = 1.37, $CHCl_3$).

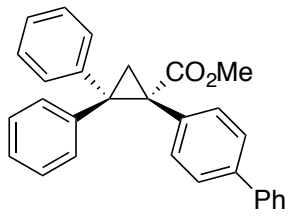
Mp: 180-182 ^{o}C; $[\alpha]^{20}_{D:}$ -224.8^{o} (*c* = 3.77, $CHCl_3$); ^{1}H NMR (400 MHz; $CDCl_3$) δ 7.44-7.42 (m, 2H), 7.29-7.22 (m, 5H), 7.13-7.11 (m, 2H), 6.99-6.93 (m, 5H), 2.56 (d, *J* = 5.6 Hz, 1H), 2.41 (d, *J* = 5.6 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 176.7,141.2, 138.9, 134.3, 133.5, 130.6, 129.7, 128.5, 128.4, 127.8, 127.1, 126.5, 121.3, 45.8, 41.9, 23.1; IR (neat): 3024, 1688, 1489, 1449; HRMS (APCI) calcd for $C_{22}H_{16}BrO_2$ $(M-H)^+$ 391.03391 found 391.03446; HPLC (testing of its corresponding methyl ester, which was made from dimethylsulfate/KOH in refluxing tetrahydrofuran): (S,S-Whelk, 5% isopropanol in hexane, 0.8 mL/min, 1 mg/mL, 60 min, UV 254 nm) retention times of 10.7 min (major) and 49.8 min (minor), 99% ee.



dirhodium tetrakis((*R*)-1-(4-bromophenyl)-2,2-diphenylcyclopropanecarboxylate) (**3.19**)

A solution of sodium rhodium carbonate $[Na_4Rh_2(CO_3)_4]$-2.5H_2O (557 mg, 1.0 equiv) and enantiopure (*R*)-1-(4-bromophenyl)-2,2-diphenylcyclopropanecarboxylic acid (**3.17**) (3.0g, 8.0 equiv) in 90 mL distilled water was refluxed for two days under argon, and then the solution was extracted with dichloromethane (100mL), and washed with saturated sodium bicarbonate (10 mL), brine (10 mL), dried over anhydrous $MgSO_4$, and concentrated under vacuum. The crude material was purified using flash column chromatography (toluene/acetonitrile = 50/1) to provide the desired catalyst (**3.19**) as a green solid (799 mg, 47%).

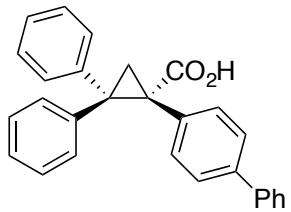
Mp: 235-237 ^oC; $[\alpha]^{20}_{D:}$ -41.7^o (*c* = 0.02, $CHCl_3$); ^1H NMR (400 MHz, $CDCl_3$): δ 7.23−7.15 (m, 7H), 6.90-6.81 (m, 7H), 2.30 (d, 1H, *J* = 5.2 Hz), 2.39 (d, 1H, *J* = 4.8 Hz); ^{13}C NMR (100 MHz, $CDCl_3$) δ 188.9, 142.4, 140.8, 135.7, 132.8, 130.6, 129.9, 129.2, 128.3, 127.9, 126.6, 126.4, 120.9, 46.9, 42.7, 23.6; IR (neat): 1577, 1490, 1447, 1397, 1379, 1277, 1156, 1076, 1010, 991, 906, 823, 777, 733; HRMS (ESI) calcd for $C_{88}H_{64}Br_4O_8$ $(M)^+$ 1769.9444 found 1769.94392. Rh_2(*S*-BTPCP)$_4$ was prepared with the same procedure, $[\alpha]^{20}_{D:}$ 140.9^o (*c* = 0.02, $CHCl_3$).



(*R*)-methyl 1-([1,1'-biphenyl]-4-yl)-2,2-diphenylcyclopropanecarboxylate (**3.21**)

To a flame-dried round bottom flask kept under a dry atmosphere of argon, was added Rh_2(*R*-DOSP)$_4$ (0.0025 equiv, 60 mg), 1,1-diphenylethlyene (**3.6**) (2.32 equiv, 5.3 g, 29 mmol), and dry degassed pentane (100 mL). A solution of freshly prepared methyl 2-([1,1'-biphenyl]-4-yl)-2-diazoacetate (**3.20**) (1.0 equiv, 3.2 g, 12.6 mmol) in dry, degassed pentane (200 mL) was added to the former solution drop-wise over 3 hours at -78 °C. The mixture was allowed to stir overnight to room temperature, and then concentrated *in vacuo*. The crude material was purified using flash column chromatography (hexanes/ethyl acetate = 45/1) to provide the desired product (**3.21**) as a white solid (4.3 g, 84%).

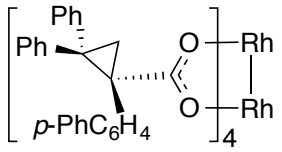
Mp: 53-55 °C; $[\alpha]^{20}_{D}$ -266.1° (*c* = 1.08, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.54-7.51 (m, 4H), 7.41-7.26 (m, 10 H), 7.04-6.94 (m, 5H), 3.37 (s, 3H), 2.72 (d, *J* = 5.6 Hz, 1H), 2.45 (d, *J* = 5.6 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 171.3, 141.9, 140.6, 139.5, 139.4, 134.7, 132.2, 129.9, 128.7, 128.6, 128.3, 127.6, 127.1, 126.9, 126.1, 52.1, 44.5, 42.8, 22.8; IR (neat): 3057, 3028, 2947, 1722, 1489, 1217; HRMS (APCI) calcd for $C_{29}H_{25}O_2$ $(M+H)^+$ 405.18491 found 405.18463; HPLC (DACHDNB, 0.5% isopropanol in hexane, 1.0 mL/min, 1 mg/mL, 30 min, UV 254 nm) retention times of 21.1 min (minor) and 23.8 min (major), >99% ee.



(*R*)-1-([1,1'-biphenyl]-4-yl)-2,2-diphenylcyclopropanecarboxylic acid (**3.22**)

To a round-bottom flask at room temperature was added (*R*)-methyl 1-([1,1'-biphenyl]-4-yl)-2,2-diphenylcyclopropanecarboxylate (**3.21**) (10.6 mmol, 4.3 g, 1.0 equiv) in dry DMSO (30 mL). ^{t}BuOK (23.4 mmol, 2.62 g, 2.2 equiv) was added in several portions over 30 minutes under argon. The reaction was monitored by TLC technique until the starting material was consumed completely. The reaction mixture was cooled with ice bath and acidified by saturated ammonium chloride aqueous (15 mL), followed by a slow addition of 1 N HCl (30 mL) with vigorous stirring until the pH value reached 3-4. Sticky solid precipitate was collected by filtration, washed with water (3 x 5 mL), dissolved in ethyl acetate (150 mL), washed with brine (3 x 10 mL), dried over anhydrous $MgSO_4$, and concentrated *in vacuo*. The crude material was purified using flash column chromatography (hexanes/ethyl acetate = from 10/1 to 5/1) to provide the desired product (**3.22**) as a white solid (2.9 g, 70%).

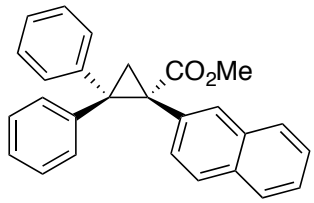
Mp: 179-180 °C; $[\alpha]^{20}_{D}$ -256.7° (*c* = 1.45, $CHCl_3$); ^{1}H NMR (400 MHz; $CDCl_3$) δ 7.51-7.48 (m, 4H), 7.40-7.26 (m, 10H), 6.99-6.92 (m, 5H), 2.60 (d, *J* = 5.6 Hz, 1H), 2.47 (d, *J* = 5.6 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 177.4, 141.5, 140.5, 139.6, 139.2, 134.2, 132.2, 129.8, 128.6, 128.4, 127.6, 127.1, 126.9, 126.2, 126.0, 45.7, 42.2, 23.2; IR (neat): 3058, 3027, 1689, 1489, 1238; HRMS (APCI) calcd for $C_{28}H_{23}O_2$ $(M+H)^+$ 391.16926 found 391.16932; HPLC (to improve the separation, the product was converted to the corresponding methyl ester prepared using dimethylsulfate/KOH in tetrahydrofuran under reflux), HPLC (DACHDNB, 0.5% isopropanol in hexane, 1.0 mL/min, 1 mg/mL, 30 min, UV 254 nm) retention times of 21.1 min (minor) and 23.6 min (major), >99% ee.



dirhodium tetrakis(*R*)-1-([1,1'-biphenyl]-4-yl)-2,2-diphenylcyclopropanecarboxylate] (**3.23**)

A solution of sodium rhodium carbonate $[Na_4Rh_2(CO_3)_4]$-$2.5H_2O$ (392 mg, 1.0 equiv) and (*R*)-1-([1,1'-biphenyl]-4-yl)-2,2-diphenylcyclopropanecarboxylic acid (**3.22**) (2.1 g, 8.0 equiv) in distilled water (60 mL) was refluxed for 1 day under argon atmosphere, and then the solution was extracted with dichloromethane (3 x 100 mL), organic extracts were combined, washed with saturated sodium bicarbonate (3 x 10 mL), 10% sodium hydroxide (3 x 10 mL), brine (3 x 10 mL), dried over anhydrous $MgSO_4$, and concentrated *in vacuo*. The crude material was purified using flash column chromatography (toluene/acetonitrile = 50/1) to provide the desired catalyst (**3.23**) as a green solid (769.9 mg, 65%).

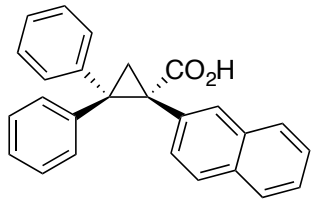
Mp: 233-235 °C; $[\alpha]^{20}_D$ 29.1° (*c* = 0.05, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.35-7.26 (m, 48H), 7.02 (d, *J* = 7.8 Hz, 8H), 6.91 (d, *J* = 7.8 Hz, 8H), 6.84 (t, *J* = 7.6 Hz, 8H), 6.77 (t, *J* = 7.2 Hz, 4H), 2.50 (d, *J* = 5.0 Hz, 4H), 1.98 (d, *J* = 5.0 Hz, 4H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 188.7, 142.8, 141.1, 140.5, 138.5, 135.5, 131.3, 129.9, 129.1, 128.6, 127.9, 127.3, 126.8, 126.7, 126.1, 125.7, 46.4, 42.7, 23.2; IR (neat): 3056, 3027, 1578, 1447, 1384, 738, 695; HRMS (ESI) calcd for $C_{112}H_{84}O_8Cl$ $(M+Cl)^+$ 1797.39703 found 1797.39840.



(*R*)-methyl 1-(naphthalen-2-yl)-2,2-diphenylcyclopropanecarboxylate (**3.25**)

To a flame-dried round bottom flask kept under a dry atmosphere of argon, was added Rh_2(*R*-DOSP)$_4$ (0.01 equiv, 474 mg), 1,1-diphenylethlyene (**3.6**) (2.32 equiv, 10.5 g, 58 mmol), and dry degassed pentane (100 mL). A solution of freshly prepared methyl 2-diazo-2-(naphthalen-2-yl)acetate (**3.24**) (1.0 equiv, 5.65 g, 25.0 mmol) in dry, degassed pentane (250 mL) was added to the former solution drop-wise over 3 hours at -40 °C. The mixture was allowed to stir overnight to room temperature, and then concentrated *in vacuo*. The crude material was purified using flash column chromatography (hexanes/ethyl acetate = 40/1) to provide the desired product (**3.25**) as a white solid (7.0 g, 74%).

Mp: 138-139 °C; $[\alpha]^{20}_{D}$ -347.9° (*c* = 1.0, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.78 (s, 1H), 7.74-7.71 (m, 1H), 7.50-7.36 (m, 4H), 7.24-7.22 (m, 1H), 7.06-7.04 (m, 2H), 6.96-6.86 (m, 3H), 3.38 (s, 3H), 2.79 (d, *J* = 5.6 Hz, 1H), 2.57 (d, *J* = 5.6 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 171.4, 141.9, 139.4, 133.6, 132.8, 132.3, 130.4, 130.2, 129.9, 128.7, 128.3, 127.7, 127.6, 127.5, 126.9, 126.7, 126.1, 125.8, 125.6, 141.9, 139.4, 133.6, 132.8, 132.2, 130.4, 130.2, 129.9, 128.7, 128.3, 127.7, 127.6, 127.5, 126.9, 126.7, 126.1, 125.8, 125.6, 52.2, 44.5, 43.2, 23.1; IR (neat): 3057, 3024, 2947, 1724, 1433, 1215; HRMS (APCI) calcd for $C_{27}H_{23}O_2$ $(M+H)^+$ 379.16926 found 379.16952; HPLC (ODH, 0.5% isopropanol in hexane, 1.0 mL/min, 1 mg/mL, 30 min, UV 254 nm) retention times of 8.6 min (major) and 9.6 min (minor), >99% ee.

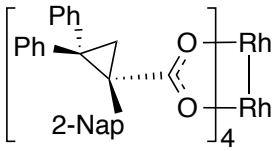


(*R*)-1-(naphthalen-2-yl)-2,2-diphenylcyclopropanecarboxylic acid (**3.26**)

To a round-bottom flask at room temperature was added (*R*)-methyl 1-(naphthalen-2-yl)-2,2-diphenylcyclopropanecarboxylate (**3.25**) (18.5 mmol, 7.0 g, 1.0 equiv) in dry DMSO (50 mL). $^{t-}$BuOK (41.0 mmol, 4.6 g, 2.2 equiv) was added in several portions over 30 minutes under argon. The reaction was monitored by TLC technique until the starting material was consumed completely. The reaction mixture was cooled with ice bath and acidified by saturated ammonium chloride aqueous (15 mL), followed by a slow addition of 1 N HCl (40 mL) with vigorous stirring until the pH value reached 3-4. Sticky solid precipitate was collected by filtration, washed with water (3 x 5 mL), dissolved in ethyl acetate (150 mL), washed with brine (3 x 10 mL), dried over anhydrous $MgSO_4$, and concentrated *in vacuo*. The crude material was purified using flash column chromatography (hexanes/ethyl acetate = from 10/1 to 4/1) to provide the desired product (**3.26**) as a white solid (4.1 g, 61%).

Mp: 195-196 °C; $[\alpha]^{20}_D$ -361.7° (*c* = 1.0, $CHCl_3$); ^{1}H NMR (400 MHz; $CDCl_3$) δ 7.80-7.76 (m, 3H), 7.65-7.59 (m, 3H), 7.53-7.46 (m, 3H), 7.42-7.34 (m, 3H), 7.11-7.09 (m, 2H), 7.0-6.9 (m, 3H), 2.73 (d, *J* = 5.2 Hz, 1H), 2.65 (d, *J* = 5.2 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 177.4, 141.5, 139.1, 133.1, 132.7, 132.3, 130.3, 130.1, 129.8, 128.6, 128.4, 127.7, 127.6, 127.5, 126.9, 126.7, 126.2, 125.8, 125.7, 42.7, 23.4; IR (neat): 3058, 1687, 1448, 1300; HRMS (APCI) calcd for $C_{26}H_{21}O_2$ $(M+H)^+$ 365.15361 found

365.15349; HPLC (to improve the separation, the product was converted to the corresponding methyl ester prepared using dimethylsulfate/KOH in tetrahydrofuran under reflux), HPLC (ODH, 0.5% isopropanol in hexane, 1.0 mL/min, 1 mg/mL, 30 min, UV 254 nm) retention times of 8.6 min (major) and 9.6 min (minor), >99% ee.

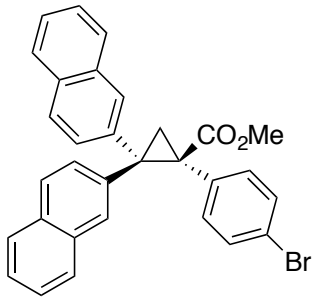


dirhodium tetrakis[(*R*)-1-(naphthalen-2-yl)-2,2-diphenylcyclopropanecarboxylate] (**3.27**)

A solution of sodium rhodium carbonate $[Na_4Rh_2(CO_3)_4]$-2.5H_2O (599.6 mg, 1.0 equiv) and (*R*)-1-(naphthalen-2-yl)-2,2-diphenylcyclopropanecarboxylic acid (**3.26**) (3.0 g, 8.0 equiv) in distilled water (60 mL) was refluxed for 2 days under argon, and then the solution was extracted with dichloromethane (3 x 100 mL), organic extracts were combined, washed with saturated sodium bicarbonate (3 x 10 mL), 10% sodium hydroxide (3 x 10 mL), brine (3 x 10 mL), dried over anhydrous $MgSO_4$, and concentrated *in vacuo*. The crude material was purified using flash column chromatography (toluene/acetonitrile = from 100/1 to 50/1) to provide the desired catalyst (**3.27**) as a green solid (989 mg, 58%).

Mp: 249-251 °C; $[\alpha]^{20}_D$ 91.2° (*c* = 0.02, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.70-7.67 (m, 8 H), 7.54 (s, 4H), 7.43-7.29 (m, 32 H), 7.24-7.21 (m, 4H), 7.10 (d, *J* = 8.4 Hz, 4H), 6.92-6.85 (m, 12 H), 6.75-6.65 (m, 12H), 2.48 (d, *J* = 4.8 Hz, 4H), 2.02 (d, *J* = 4.8 Hz, 4H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 188.9, 142.6, 140.9, 134.5, 132.6, 132.1, 130.9, 129.8, 129.0, 128.2, 128.1, 127.7, 127.6, 127.4, 127.3, 126.2, 126.1, 125.7, 125.4, 125.3,

46.6, 43.1, 23.5; IR (neat): 3056, 3023, 1579, 1389, 1348, 908, 744, 755, 704; HRMS (ESI) calcd for $C_{104}H_{76}O_8Cl$ $(M+Cl)^+$ 1693.33443 found 1693.33556.

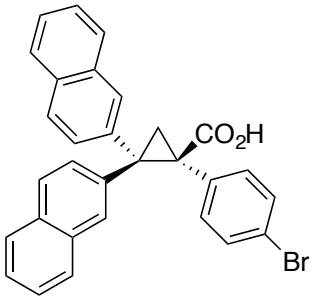


(*S*)-methyl 1-(4-bromophenyl)-2,2-di(naphthalen-2-yl)cyclopropanecarboxylate (**3.33**)

To a flame-dried round bottom flask kept under a dry atmosphere of argon, was added Rh_2(*S*-DOSP)$_4$ (0.01 equiv, 103 mg), 2,2'-(ethene-1,1-diyl)dinaphthalene (**3.32**) (2.3 equiv, 3.5 g, 12.5 mmol), and dry degassed pentane (50 mL). A solution of freshly prepared methyl 2-(4-bromophenyl)-2-diazoacetate (**3.17**) (1.0 equiv, 1.38 g, 5.43 mmol) in dry, degassed pentane (100 mL) was added to the former solution drop-wise over 3 hours at room temperature. The mixture was allowed to stir overnight to room temperature, and then concentrated *in vacuo*. The crude material was purified using flash column chromatography (hexanes/ethyl acetate = 45/1) to provide the desired product (**3.33**) as a white solid (1.7 g, 62%).

Mp: 73-75 °C; $[\alpha]^{20}_D$ 257.6° (*c* = 0.76, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.17 (s, 1H), 7.99-7.91 (m, 3 H), 7.82-7.78 (m, 1H), 7.72-7.66 (m, 3H), 7.59-7.52 (m, 3H), 7.47-7.32 (m, 7H), 3.46 (s, 3H), 3.01 (d, *J* = 5.6 Hz, 1H), 2.73 (d, *J* = 5.6 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 170.8, 139.0, 136.8, 134.7, 133.4, 133.2, 132.7, 132.3, 131.6, 130.6, 128.7, 128.4, 128.1, 127.9, 127.7, 127.6, 127.5, 127.2, 126.6, 126.1, 125.8, 125.7, 121.2, 52.2, 44.8, 42.6, 22.9; IR (neat): 3054, 2948, 1723, 1215; HRMS (APCI) calcd for

$C_{31}H_{22}O_2Br$ $(M-H)^+$ 505.08086 found 505.08075; HPLC (ODH, 3% isopropanol in hexane, 1.0 mL/min, 1 mg/mL, 30 min, UV 254 nm) retention times of 7.4 min (major) and 9.3 min (minor), 98% ee.

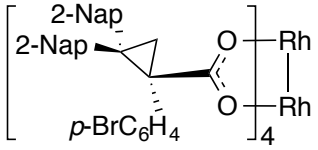


(*S*)-1-(4-bromophenyl)-2,2-di(naphthalen-2-yl)cyclopropanecarboxylic acid (**3.34**)

To a round-bottom flask at room temperature was added (*S*)-methyl 1-(4-bromophenyl)-2,2-di(naphthalen-2-yl)cyclopropanecarboxylate (**3.33**) (1.97 mmol, 1.0 g, 1.0 equiv) in dry DMSO (15 mL). ^{t}BuOK (4.54 mmol, 509 mg, 2.3 equiv) was added in several portions over 30 minutes under argon. The reaction was monitored by TLC technique until the starting material was consumed completely. The reaction mixture was cooled with ice bath and acidified by saturated ammonium chloride aqueous (15 mL), followed by a slow addition of 1 N HCl (30 mL) with vigorous stirring until the pH value reached 3-4. Sticky solid precipitate was collected by filtration, washed with water (3 x 5 mL), dissolved in ethyl acetate (150 mL), washed with brine (3 x 10 mL), dried over anhydrous $MgSO_4$, and concentrated *in vacuo*. The crude material was purified using flash column chromatography (hexanes/ethyl acetate = from 10/1 to 4/1) to provide the desired product (**3.34**) as a white solid (300 mg, 31%).

Mp: 198-200 °C; $[\alpha]^{20}_D$ 282.7° (*c* = 1.28, $CHCl_3$); ^{1}H NMR (400 MHz; $CDCl_3$) δ 8.00 (s, 1H), 7.91-7.81 (m, 4H), 7.66-7.49 (m, 5H), 7.39-7.36 (m, 2H), 7.29-7.20 (m, 6H), 2.72

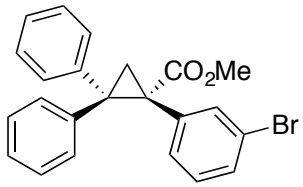
(d, J = 5.2 Hz, 1H), 2.64 (d, J = 5.2 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ176.3, 138.7, 136.7, 134.3, 133.4, 132.8, 132.4, 11.8, 130.7, 128.4, 128.2, 127.9, 127.8, 127.6, 127.4, 127.3, 126.7, 126.1, 125.9, 121.4, 46.3, 41.9, 23.7; IR (neat): 3054, 3019, 2948, 1689, 1631, 1559, 1489, 1434, 1215, 1011, 756; HRMS (ESI) calcd for $C_{30}H_{20}O_2Br$ $(M\text{-}H)^+$ 491.06521 found 491.06488; HPLC (recrystallization, to improve the separation, the product was converted to the corresponding methyl ester prepared using dimethylsulfate/KOH in tetrahydrofuran under reflux) (ODH, 3% isopropanol in hexane, 1.0 mL/min, 1 mg/mL, 30 min, UV 254 nm) retention times of 7.3 min (major) and 9.1 min (minor), 99.5% ee.



dirhodium tetrakis [(*S*)-1-(4-bromophenyl)-2,2-di(naphthalen-2-yl)cyclopropanecarboxylate] (**3.35**)

A solution of sodium rhodium carbonate $[Na_4Rh_2(CO_3)_4]$-2.5H_2O (44.4 mg, 1.0 equiv) and (*S*)-1-(4-bromophenyl)-2,2-di(naphthalen-2-yl)cyclopropanecarboxylic acid (**3.34**) (300 mg, 8.0 equiv) in 30 mL distilled water was refluxed for 1 days under argon, and then the solution was extracted with dichloromethane (3 x 100 mL), organic extracts were combined, washed with saturated sodium bicarbonate (3 x 10 mL), 10% sodium hydroxide (3 x 10 mL), brine (3 x 10 mL), dried over anhydrous $MgSO_4$, and concentrated *in vacuo*. The crude material was purified using flash column chromatography (toluene/acetonitrile = from 100/1 to 50/1) to provide the desired catalyst **(3.35**) as a green solid (77.9 mg, 47%).

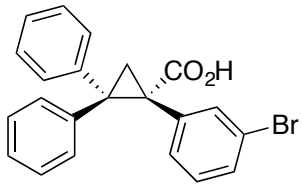
Mp: 247-248 °C; $[\alpha]^{20}_{D}$ 122.3° (*c* = 0.06, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.84-7.79 (m, 8H), 7.72-7.66 (m, 8H), 7.56 (t, *J* = 7.2 Hz, 8H), 7.50-7.47 (m, 8H), 7.38-7.24 (m, 20h), 7.17 (d, *J* = 8.0 Hz, 8H), 6.99 (d, *J* = 8.8 Hz, 4H), 6.83 (d, *J* = 8.0 Hz, 8H), 2.08 (d, *J* = 4.8 Hz, 4H), 1.84 (d, *J* = 4.8 Hz, 4H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 189.1, 140.2, 139.1, 135.9, 133.7, 133.1, 132.7, 132.4, 131.9, 130.7, 128.9, 128.6, 128.4, 128.3, 128.0, 127.9, 127.6, 127.5, 127.4, 126.0, 125.9, 125.8, 120.9, 46.8, 42.8, 23.8; IR (neat): 3055, 2924, 2852, 1582, 1383, 755; HRMS (ESI) calcd for $C_{120}H_{80}O_8ClBr_4Rh_2$ $(M+Cl)^+$ 2205.03907 found 2205.03602.



(*R*)-methyl 1-(3-bromophenyl)-2,2-diphenylcyclopropanecarboxylate (**3.29**)

To a flame-dried round bottom flask kept under a dry atmosphere of argon, was added Rh_2(*R*-DOSP)$_4$ (0.005 equiv, 153 mg), 1,1-diphenylethlyene (**3.6**) (2.5 equiv, 7.25 g, 40.3 mmol), and dry degassed pentane (100 mL). A solution of freshly prepared methyl 2-(3-bromophenyl)-2-diazoacetate (**3.28**) (1.0 equiv, 4.1 g, 16.1 mmol) in dry, degassed pentane (150 mL) was added to the former solution drop-wise over 2 hours at 0 °C. The mixture was allowed to stir overnight to room temperature, and then concentrated *in vacuo*. The crude material was purified using flash column chromatography (hexanes/ethyl acetate = 50/1) to provide the desired product (**3.29**) as a white solid (6.0 g, 92%).

Mp: 85-87 °C; $[\alpha]^{20}_{D}$ -38.3° (*c* = 0.99, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.66-7.61 (m, 3H), 7.46-7.30 (m, 5H), 7.16-7.04 (m, 6H), 3.44 (s, 3H), 2.81 (d, *J* = 6.0 Hz), 2.53 (d, *J* = 6.0 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 170.5, 141.5, 138.8, 137.9, 134.6, 130.5, 129.8, 129.6, 128.8, 128.4, 128.2, 127.6, 126.9, 126.2, 121.2, 52.0, 44.5, 42.3, 22.4; IR (neat): 2988, 2951, 2869, 1725, 1218, 1142, 703; HRMS (APCI) calcd for $C_{23}H_{20}O_2Br$ $(M+H)^+$ 407.06412 found 407.06510; HPLC (S,S-whelk, 3% isopropanol in hexane, 1.0 mL/min, 1 mg/mL, 30 min, UV 230 nm) retention times of 7.93 min (major) and 20.7 min (minor), >99% ee.

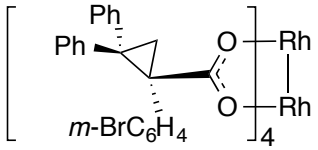


(*R*)-1-(3-bromophenyl)-2,2-diphenylcyclopropanecarboxylic acid (**3.30**)

To a round-bottom flask at room temperature was added (*R*)-methyl 1-(3-bromophenyl)-2,2-diphenylcyclopropanecarboxylate (**3.29**) (14.8 mmol, 6.0 g, 1.0 equiv) in dry DMSO (60 mL). $^{t-}$BuOK (36.9 mmol, 4.14 g, 2.5 equiv) was added in several portions over 1 hour under argon. The reaction was monitored by TLC technique until the starting material was consumed completely. The reaction mixture was cooled with ice bath and acidified by saturated ammonium chloride aqueous (15 mL), followed by a slow addition of 1 N HCl with vigorous stirring until the pH value reached 3-4. Sticky solid precipitate was collected by filtration, washed with water (3 x 5 mL), dissolved in ethyl acetate (150 mL), washed with brine (3 x 10 mL), dried over anhydrous $MgSO_4$, and concentrated *in vacuo*. The crude material was purified using flash column chromatography

(hexanes/ethyl acetate = from 10/1 to 4/1) to provide the desired product (**3.30**) as a white solid (3.4 g, 59% yield, 97% ee, then, recrystallization in hexanes/ether to improve the ee > 99%, 2.8g).

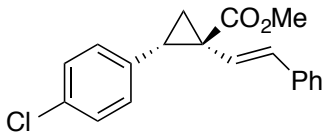
Mp: 174-175 °C; $[\alpha]^{20}_{D}$ -187.9° (*c* = 1.06, $CHCl_3$); ^{1}H NMR (400 MHz; $CDCl_3$) δ 7.49-7.47 (m, 3H), 7.36-7.30 (m, 3H), 7.25-7.18 (m, 2H), 7.06-6.96 (m, 6H), 2.58 (d, *J* = 5.8 Hz, 1H), 2.46 (d, *J* = 5.8 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 176.8, 141.1, 138.7, 137.5, 134.8, 130.6, 130.1, 129.7, 128.9, 128.5, 128.4, 127.8, 127.1, 126.5, 121.3, 45.9, 41.9, 23.1; IR (neat): 3058, 3023, 2877, 2869, 1691, 1477, 1407, 698; HRMS (APCI) calcd for $C_{22}H_{18}O_2Br$ $(M+H)^+$ 393.04847 found 393.04909; HPLC (ADH, 5% isopropanol in hexane, 1.0 mL/min, 1 mg/mL, 30 min, UV 230 nm) retention times of 14.7 min (major) and 19.9 min (minor), >99% ee.



dirhodium tetrakis[(*R*)-1-(3-bromophenyl)-2,2-diphenylcyclopropanecarboxylate] (**3.31**)

A solution of sodium rhodium carbonate $[Na_4Rh_2(CO_3)_4]$-2.5H_2O (116.4 mg, 0.2 mmol, 1.0 equiv) and (*R*)-1-(3-bromophenyl)-2,2-diphenylcyclopropanecarboxylic acid (**3.29**) (625 mg, 1.6 mmol, 8.0 equiv) in 50 mL distilled water was refluxed for 2.5 days under argon, and then the solution was extracted with dichloromethane (3 x 50 mL), organic extracts were combined, washed with saturated sodium bicarbonate (3 x 10 mL), brine (3 x 10 mL), dried over anhydrous $MgSO_4$, and concentrated *in vacuo*. The crude material was purified using flash column chromatography (toluene/acetonitrile = from 100/1 to 50/1) to provide the desired catalyst (**3.31**) as a green solid (220 mg, 62%).

^{1}H NMR (400 MHz, $CDCl_3$): δ 7.30-7.28 (m, 17H), 7.21-7.16 (m, 14H), 6.99-6.89 (m, 18H), 6.83-6.81 (m, 5H), 2.30 (d, *J* = 5.0 Hz, 4H), 2.01 (d, *J* = 5.0 Hz, 4H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 188.4, 141.8, 140.2, 139.1, 133.2, 130.5, 129.8, 129.3, 128.9, 128.7, 127.9, 127.6, 126.3, 126.1, 121.1, 46.3, 42.8, 23.8; IR (neat): 3024, 2925, 1580, 1383, 703; HRMS (NSI) calcd for $C_{88}H_{65}O_8Br_3{}^{81}BrRh_2$ $(M+H)^+$ 1772.94971 found 1772.95690.

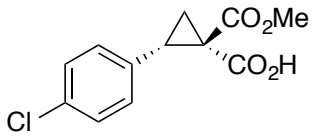


(1*S*,2*S*)-methyl 2-(4-chlorophenyl)-1-((*E*)-styryl)cyclopropanecarboxylate (**3.46**)

To a flame-dried round bottom flask kept under a dry atmosphere of argon, was added Rh_2(*S*-DOSP)$_4$ (0.005 equiv, 57 mg), 1-chloro-4-vinylbenzene (**3.45**) (2.5 equiv, 2.31 g, 16.8 mmol), and dry degassed pentane (60 mL). A solution of freshly prepared methyl (*E*)-2-diazo-4-phenylbut-3-enoate (**3.1**) (1.0 equiv, 1.35 g, 6.7 mmol) in dry, degassed pentane (50 mL) was added to the former solution drop-wise over 2 hours at 0 °C. The mixture was allowed to stir overnight to room temperature, and then concentrated *in vacuo*. The crude material was purified using flash column chromatography (hexanes/ethyl acetate = 60/1) to provide the desired product **3.46** as a white solid (1.7 g, 81%).

Mp: 76-78 ^{o}C; $[\alpha]^{20}_{D:}$ -120.4 ^{o} (*c* = 1.0, $CHCl_3$); ^{1}H NMR (400 MHz; $CDCl_3$) δ 7.25-7.15 (m, 7H), 7.04-7.02 (m, 2H), 6.34 (d, *J* = 15.9 Hz, 1H), 6.12 (d, *J* = 16.4 Hz, 1H), 3.73 (s, 3H), 2.94 (dd, *J* = 9.0, 7.5 Hz, 1H), 2.02-1.99 (m, 1H), 1.77 (dd, *J* = 7.0, 5.2 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 173.8, 136.7, 134.1, 133.4, 132.5, 130.3, 128.4, 128.1, 127.5, 126.2, 123.5, 52.4, 34.0, 33.4, 18.5; IR (film): 3026, 2951, 2360, 2343, 1721, 1249;

HRMS (APCI) calcd for $C_{19}H_{19}ClO_2$ $(M+H)^+$ 313.09953 found 313.09888; HPLC (Chiralcel S,S-Whelk, 1.5% isopropanol in hexane, 0.7 mL/min, 1 mg/mL, 30 min, UV 254 nm) retention times of 17.1 min (minor) and 23.7 min (minor), 98% ee.

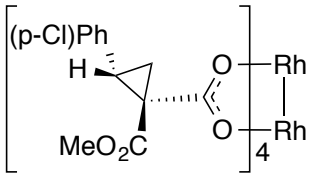


(1*R*,2*S*)-2-(4-chlorophenyl)-1-(methoxycarbonyl)cyclopropanecarboxylic acid (**3.47**)

To a round-bottom flask at room temperature was added sodium periodate (46.8 mmol, 10.0 g, 9.0 equiv) in water (150 mL), which was treated with potassium permanganate (1.04 mmol, 164.3 mg, 0.2 equiv). The resulting solution stirred for another 1 hour at room temperature. The purple suspension was then treated with potassium carbonate (5.5 mmol, 753 mg, 1.05 equiv), *tert*-butanol (50 mL). A solution of (1*S*,2*S*)-methyl 2-(4-chlorophenyl)-1-((*E*)-styryl)cyclopropanecarboxylate (**3.46**) (5.2 mmol, 1.7 g, 1.0 equiv) in *tert*-butanol (50 mL) was added into the former solution. After stirring 5 hours, ethylene glycol (22.8 mmol, 1.28 mL, 4.4 equiv) was added and stirred another 1 hour to destroy the remaining oxidant. Then, the reaction mixture was washed with water (3 x 5 mL), dissolved in ethyl acetate (150 mL), washed with brine (3 x 10 mL), dried over anhydrous $MgSO_4$, and concentrated *in vacuo*. The crude material was purified using flash column chromatography (hexanes/ethyl acetate 10/1) to provide the desired product (**3.47**) as a white solid (468 mg, 35%).

Mp: 109-110 ^oC; $[\alpha]^{20}_{D:}$ -119.9^o (*c* = 1.0, $CHCl_3$); ^1H NMR (400 MHz; $CDCl_3$) δ 10.59 (br, 1H), 7.25-7.14 (m, 4H), 3.81 (s, 3H), 3.26 (t, *J* = 9.0 Hz, 1H), 2.32 (dd, *J* = 8.5, 4.9 Hz, 1H), 2.03 (dd, *J* = 9.3, 5.0 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 172.9, 167.9,

133.5, 131.8, 130.4, 128.2, 53.4, 36.7, 34.7, 20.6; IR (film): 3016, 2969, 1738, 1366, 1217; HRMS (APCI) calcd for $C_{12}H_{12}ClO_4$ $(M+H)^+$ 255.04241 found 255.04178; HPLC (AD-H, 20% isopropanol in hexane, 1.0 mL/min, 1 mg/mL, 60 min, UV 254 nm) retention times of 9.4 min (major) and 11.5 min (minor), 99% ee.

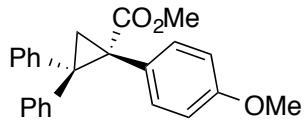


dirhodium tetrakis((1*R*,2*S*)-2-(4-chlorophenyl)-1-(methoxycarbonyl)cyclopropanecarboxylate) (**3.48**)

A solution of sodium rhodium carbonate $[Na_4Rh_2(CO_3)_4]$-$2.5H_2O$ (129 mg, 0.22 mmol, 1.0 equiv) and (*R*)-(1*R*,2*S*)-2-(4-chlorophenyl)-1-(methoxycarbonyl)cyclopropanecarboxylic acid (**3.47**) (452 mg, 1.78 mmol, 8.0 equiv) in 15 mL distilled water was refluxed for overnight under argon, and then the solution was extracted with dichloromethane (3 x 10 mL), organic extracts were combined, washed with saturated sodium bicarbonate (3 x 10 mL), 10% sodium hydroxide (3 x 10 mL), brine (3 x 10 mL), dried over anhydrous $MgSO_4$, and concentrated *in vacuo*. The crude material was purified using flash column chromatography (toluene/acetonitrile =from 100/1 to 50/1) to provide the desired catalyst **(3.48**) as a green solid (32.5 mg, 12%).

Mp: 216-218 ^oC; $[\alpha]^{20}_D$ -43.5° (*c* = 0.09, $CHCl_3$); ^1H NMR (400 MHz, $CDCl_3$): δ 7.14 (d, *J* = 8.5 Hz, 8H), 6.88 (d, *J* = 8.5 Hz, 8H), 3.67 (s, 12H), 2.90 (t, *J* = 9.0 Hz, 1H), 1.61 (dd, *J* = 8.4, 5.0 Hz, 1H), 1.53 (dd, *J* = 9.5, 4.9 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 184.3, 169.5, 133.3, 132.6, 130.2, 128.0, 52.6, 37.9, 32.8, 20.9; IR (film): 2951, 1725,

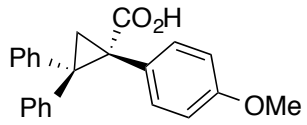
1589, 1413, 1281, 1146; HRMS (ESI) calcd for $C_{50}H_{40}O_{18}Cl_4F_3Rh_2$ $(M+CF_3COO)^+$ 1330.9030 found 1330.90394.



(*R*)-methyl 1-(4-methoxyphenyl)-2,2-diphenylcyclopropanecarboxylate (**3.36**)

To a flame-dried round bottom flask kept under a dry atmosphere of argon, was added Rh_2(*R*-DOSP)$_4$ (0.005 equiv, 177 mg), 1,1-diphenylethlyene (**3.6**) (2.32 equiv, 3.9 g, 46.4 mmol), and dry degassed pentane (100 mL). A solution of freshly prepared methyl 2-diazo-2-(4-methoxyphenyl)acetate (1.0 equiv, 1.92 g, 9.32 mmol) in dry, degassed pentane (100 mL) was added to the former solution drop-wise over 2 hours at -40 °C, and the mixtures was allowed to stir overnight to room temperature, and then concentrated *in vacuo*. The crude material was purified using flash column chromatography (hexanes/ethyl acetate = 20/1) to provide the desired product (**3.36**) as a white foam (2.4 g, 73%).

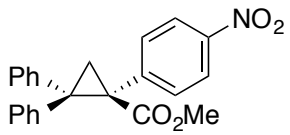
Mp: 110-112 ^oC; $[\alpha]^{20}_{D:}$ -267.6^o (*c* = 1.0, $CHCl_3$); ^1H NMR (400 MHz; $CDCl_3$) δ 7.46-7.44 (m, 2H), 7.30-7.27 (m, 2H), 7.22-7.18 (m, 3H), 6.98-6.89 (m, 5H), 6.65-6.62 (m, 2H), 3.67 (s, 3H), 3.30 (s, 3H), 2.62 (d, , *J* = 5.5 Hz, 1H), 2.32 (d, *J* = 5.5 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 171.7, 158.3, 142.0, 139.7, 132.9, 129.9, 128.7, 128.3, 127.7, 127.6, 126.9, 126.0, 112.8, 55.0, 52.2, 44.4, 42.4, 22.9; IR (film): 3025, 1723, 1514；HRMS (APCI) calcd for $C_{24}H_{23}O_3$ $(M+H)^+$ 359.16417 found 359.16420; HPLC (ODH, 1.0% isopropanol in hexane, 0.5 mL/min, 1 mg/mL, 30 min, UV 254 nm) retention times of 22.9 min (minor) and 25.7 min (minor), 99% ee.



(*R*)-1-(4-methoxyphenyl)-2,2-diphenylcyclopropanecarboxylic acid (**3.37**)

To a round-bottom flask at room temperature was added (*R*)-methyl 1-(4-methoxyphenyl)-2,2-diphenylcyclopropanecarboxylate (**3.36**) (6.7 mmol, 2.4 g, 1.0 equiv) in dry DMSO (20 mL). ^{t}BuOK (14.7 mmol, 1.7 g, 2.2 equiv) was added in several portions over 30 minutes under argon. The reaction was monitored by TLC technique until the starting material was consumed completely. The reaction mixture was cooled with ice bath and acidified by saturated ammonium chloride aqueous (15 mL), followed by a slow addition of 1 N HCl (30 mL) with vigorous stirring until the pH value reached 3-4. Sticky solid precipitate was collected by filtration, washed with water (3 x 5 mL), dissolved in ethyl acetate (150 mL), washed with brine (3 x 10 mL), dried over anhydrous $MgSO_4$, and concentrated *in vacuo*. The crude material was purified using flash column chromatography (hexanes/ethyl acetate = from 10/1 to 4/1) to provide the desired product (**3.37**) (1.3 g, 56%).

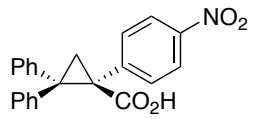
$[\alpha]^{20}_{D:}$ -252.8 ^{o} (*c* = 1.27, $CHCl_3$); ^{1}H NMR (400 MHz; $CDCl_3$) δ 7.44-7.42 (m, 2H), 7.27-7.21 (m, 3H), 7.15-7.13 (m, 2H), 6.94-6.88 (m, 5H), 6.62 (d, *J* = 8.5 Hz, 2H), 3.61 (s, 3H), 2.51 (d, *J* = 5.5 Hz, 1H), 2.35 (d, *J* = 5.2 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 177.6, 158.3, 141.6, 139.4, 132.8, 129.8, 128.6, 128.3, 127.5, 127.2, 126.8, 126.1, 112.8, 54.9, 45.5, 41.8, 23.3; IR (film): 3024, 2836, 1689, 1514, 1248; HRMS (APCI) calcd for $C_{23}H_{19}O_3$ $(M-H)^+$ 343.13397 found 343.13383; HPLC test of corresponding methyl ester (ODH, 1.0% isopropanol in hexane, 0.5 mL/min, 1 mg/mL, 30 min, UV 254 nm) retention times of 22.9 min (minor) and 25.7 min (minor), 99% ee.



(*S*)-methyl 1-(4-nitrophenyl)-2,2-diphenylcyclopropanecarboxylate (**3.38**)

To a flame-dried round bottom flask kept under a dry atmosphere of argon, was added Rh_2(*S*-DOSP)$_4$ (0.01 equiv, 436 mg), 1,1-diphenylethlyene (**3.6**) (2.3 equiv, 9.6 g), and dry degassed pentane (50 mL). A solution of freshly prepared methyl 2-diazo-2-(4-nitrophenyl)acetate (1.0 equiv, 23 mmol, 5.1 g) in dry, degassed pentane (300 mL) was added to the former solution drop-wise over 3 hours at room temperature. The mixture was allowed to stir overnight, and then concentrated *in vacuo*. The crude material was purified using flash column chromatography (hexanes/ethyl acetate = 30/1) to provide the desired product (**3.38**) (8.0 g, 93%).

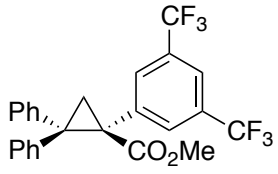
$[\alpha]^{20}_D$ 215.9° (*c* = 1.12, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.99-7.97 (m, 2H), 7.52-7.48 (m, 4H), 7.36-7.33 (m, 2H), 7.28-7.24 (m, 1H), 7.00-6.95 (m, 5H), 3.36 (s, 3H), 2.76 (d, *J* = 5.8 Hz, 1H), 2.51 (d, *J* = 5.8 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 170.2, 146.6, 143.4, 141.3, 138.6, 132.7, 129.6, 128.4, 127.9, 127.2, 126.7, 122.6, 52.3, 45.3, 42.4, 22.6; IR (neat): 3025, 1726, 1519; HRMS (APCI) calcd for $C_{23}H_{18}NO_4$ $(M\text{-}H)^+$ 372.12413 found 372.12465; HPLC (ODH, 3.0% isopropanol in hexane, 1.0 mL/min, 1 mg/mL, 30 min, UV 254 nm) retention times of 13.3 min (major) and 14.9 min (minor), 94% ee.



(*S*)-1-(4-nitrophenyl)-2,2-diphenylcyclopropanecarboxylic acid (**3.39**)

To a round-bottom flask at room temperature was added (*S*)-methyl 1-(4-nitrophenyl)-2,2-diphenylcyclopropanecarboxylate (**3.38**) (21 mmol, 8.0 g, 1.0 equiv) in dry DMSO (25 mL). ^{t}BuOK (53.6 mmol, 6.0 g, 2.5 equiv) was added in several portions over 45 minutes under argon atmosphere. The reaction was monitored by TLC technique until the starting material was consumed completely. The reaction mixture was cooled with ice bath and acidified by saturated ammonium chloride aqueous (150 mL), followed by a slow addition of 1 N HCl (100 mL) with vigorous stirring until the pH value reached 3-4. Sticky solid precipitate was collected by filtration, washed with water (3 x 50 mL), dissolved in ethyl acetate (250 mL), washed with brine (3 x 50 mL), dried over anhydrous $MgSO_4$, and concentrated *in vacuo*. The crude material was purified using flash column chromatography (hexanes/ethyl acetate = from 10/1 to 4/1) to provide the desired product (**3.39**) (2.76 g, 37%).

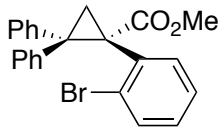
^{1}H NMR (400 MHz, $CDCl_3$) δ 7.96 (d, *J* = 8.8 Hz, 2H), 7.47-7.42 (m, 4H), 7.30-7.23 (m, 3H), 6.99-6.96 (m, 5H), 2.66 (d, *J* = 6.0 Hz, 1H), 2.54 (d, *J* = 6.0 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 175.9, 146.6, 142.8, 140.7, 138.2, 132.7, 129.5, 128.5, 128.4, 128.0, 127.2, 126.8, 122.5, 46.6, 41.9, 23.1; IR (neat): 3025, 1695, 1520; HRMS (APCI) calcd for $C_{22}H_{18}NO_4$ $(M+H)^+$ 360.12303 found 360.12364; HPLC (to test of corresponding of methyl ester, ODH, 3.0% isopropanol in hexane, 1.0 mL/min, 1 mg/mL, 30 min, UV 254 nm) retention times of 13.3 min (major) and 14.9 min (minor), 0% ee.



(*S*)-methyl 1-(3,5-bis(trifluoromethyl)phenyl)-2,2-diphenylcyclopropanecarboxylate (**3.40**)

To a flame-dried round bottom flask kept under a dry atmosphere of argon, was added Rh_2(*S*-DOSP)$_4$ (0.005 equiv, 169.7 mg), 1,1-diphenylethlyene (**3.6**) (2.5 equiv, 8.0 g), and dry degassed pentane (50 mL). A solution of freshly prepared methyl 2-(3,5-bis(trifluoromethyl)phenyl)-2-diazoacetate (1.0 equiv, 17.9 mmol, 5.6 g) in dry, degassed pentane (300 mL) was added to the former solution drop-wise over 2 hours at room temperature. The mixture was allowed to stir overnight, and then concentrated *in vacuo*. The crude material was purified using flash column chromatography (hexanes/ethyl acetate = 30/1) to provide the desired product **142** (7.6 g, 92%).

^{1}H NMR (400 MHz, $CDCl_3$) δ 7.72 (s, 2H), 7.57 (S, 1H), 7.50-7.48 (m, 2H), 7.36-7.33 (m 2H), 7.27-7.26 (m, 2H), 7.00-6.99 (m, 4H), 3.38 (s, 3H), 2.74 (d, *J* = 6.0 Hz, 1H), 2.50 (d, *J* = 6.0 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 170.2, 132.1, 131.9, 131.1, 130.7, 130.5, 130.1, 129.9, 129.6, 128.8, 128.5, 128.3, 128.1, 127.9, 127.7, 127.5, 127.3, 127.0, 126.9, 124.6, 121.9, 120.9, 120.8, 120.7, 52.4, 45.3, 42.0, 22.3; IR (neat): 3027, 1724, 1275; HRMS (APCI) calcd for $C_{25}H_{17}F_6O_4$ $(M-H)^+$ 463.11382 found 463.11345; HPLC (SS-WHELK, 0.5% isopropanol in hexane, 0.5 mL/min, 1 mg/mL, 30 min, UV 254 nm) retention times of 9.5 min (minor) and 10.6 min (major), 37% ee.

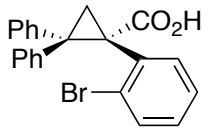


(*S*)-methyl 1-(2-bromophenyl)-2,2-diphenylcyclopropanecarboxylate (**3.41**)

To a flame-dried round bottom flask kept under a dry atmosphere of argon, was added Rh_2(*S*-PTAD)$_4$ (0.01 equiv, 282 mg), 1,1-diphenylethlyene (**3.6**) (5.0 equiv, 16.3 g, 90.6 mmol), and dry degassed pentane (100 mL). A solution of freshly prepared methyl 2-(2-

bromophenyl)-2-diazoacetate (1.0 equiv, 4.6 g, 18.1 mmol) in dry, degassed pentane (100 mL) was added to the former solution drop-wise over 2.0 hours at 0 °C. The mixture was allowed to stir overnight to room temperature, and then concentrated *in vacuo*. The crude material was purified using flash column chromatography eluting (hexanes/ethyl acetate = 50/1) to provide the desired product (**3.41**) as a white solid (6.8 g, 93%).

Mp: 132-134 °C; $[\alpha]^{20}_{D}$ -83.6° (*c* = 1.80, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.72-7.43 (m, 6H), 7.27-6.99 (m, 8H), 7.04-6.94 (m, 5H), 3.49 (s, 3H), 3.06 (br, 1H), 2.66 (d, *J* = 6.0 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 170.3, 141.1, 138.9, 135.5, 132.6, 130.2, 128.4, 128.2, 128.1, 127.1, 126.8, 126.0, 125.9, 52.1, 45.1, 43.8, 26.7; IR (neat): 3058, 3024, 2948, 1729, 1497, 1449, 1431, 1299, 1216, 1142, 1023, 749, 703; HRMS (APCI) calcd for $C_{23}H_{20}O_2Br$ $(M+H)^+$ 407.06412 found 407.06510; HPLC (S,S-whelk, 1 % isopropanol in hexane, 0.5 mL/min, 1 mg/mL, 30 min, UV 230 nm) retention times of 14.4 min (major) and 38.5 min (minor), >99% ee.

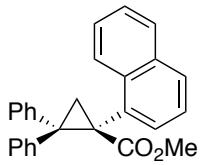


(*S*)-1-(2-bromophenyl)-2,2-diphenylcyclopropanecarboxylic acid (**3.42**)

To a round-bottom flask at room temperature was added (*S*)-methyl 1-(2-bromophenyl)-2,2-diphenylcyclopropanecarboxylate (**3.41**) (16.7 mmol, 6.8 g, 1.0 equiv) in dry DMSO (100 mL). ^{t}BuOK (41.9 mmol, 4.69 g, 2.5 equiv) was added in several portions over 1 hour under argon atmosphere. The reaction was monitored by TLC technique until the starting material was consumed completely. The reaction mixture was cooled with ice bath and acidified by saturated ammonium chloride aqueous (15 mL), followed by a slow

addition of 1 N HCl with vigorous stirring until the pH value reached 3-4. Sticky solid precipitate was collected by filtration, washed with water (3 x 5 mL), dissolved in ethyl acetate (150 mL), washed with brine (3 x 10 mL), dried over anhydrous $MgSO_4$, and concentrated *in vacuo*. The crude material was purified using flash column chromatography (hexanes/ethyl acetate = from 10/1 to 4/1) to provide the desired product (**3.42**) as a white solid (5.2 g, 79%).

Mp: 108-110 °C; $[\alpha]^{20}_D$ -65.5° (*c* = 0.95, $CHCl_3$); ^{1}H NMR (400 MHz; $CDCl_3$) δ 7.49 (br, 3H), 7.40-7.31 (m, 3H), 7.01 (br, 5H), 6.80-6.79 (m, 3H), 2.80 (br, 1H), 2.52 (d, *J* = 5.2 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 176.6, 140.8, 138.9, 136.1, 135.1, 132.8, 130.3, 128.7, 128.4, 128.3, 127.4, 127.1, 126.2, 46.4, 43.8, 27.3; IR (neat): 2974, 2866, 1690, 1496, 1297, 1024, 748; HRMS (APCI) calcd for $C_{22}H_{16}O_2Br$ $(M-H)^+$ 391.03392 found 391.03391; HPLC (ADH, 5% isopropanol in hexane, 1.0 mL/min, 1 mg/mL, 30 min, UV 254 nm) retention times of 17.8 min (major) and 21.1 min (minor), >99% ee.

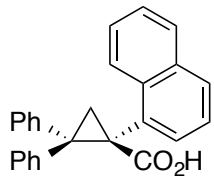


(*S*)-methyl 1-(naphthalen-1-yl)-2,2-diphenylcyclopropanecarboxylate (**3.43**)

To a flame-dried round bottom flask kept under a dry atmosphere of argon, was added Rh_2(*S*-DOSP)$_4$ (0.005 equiv, 360 g), 1,1-diphenylethlyene (**3.6**) (2.3 equiv, 15.7 g), and dry degassed pentane (30 mL). A solution of freshly prepared methyl 2-diazo-2-(naphthalen-1-yl)acetate (1.0 equiv, 8.6 g) in dry, degassed pentane (300 mL) was added to the former solution drop-wise over 5.0 hours at room temperature. The mixture was allowed to stir overnight, and then concentrated *in vacuo*. The crude material was

purified using flash column chromatography (hexanes/ethyl acetate 30/1) to provide the desired product (**3.43**) as a white solid (10.8 g, 75%).

Mp: 142-144 °C; $[\alpha]^{20}_{D}$ 408° (*c* = 1.0, $CHCl_3$); ^{1}H NMR (400 MHz, CDCl3) δ 8.27 (d, *J* = 8.4 Hz, 1H), 7.75-6.89 (m, 14H), 6.69-6.67 (m, 2H); 3.31 (s, 3H), 3.06 (br, 1H), 2.45 (br, 1H); ^{13}C NMR (100 MHz, CDCl3) δ 171.5, 141.4, 139.6, 133.5, 133.2, 130.4, 128.2, 127.7, 127.0, 126.9, 125.8, 125.1, 124.5, 52.2, 43.6, 41.6, 26.3; IR (neat): 3057, 2948, 1720, 1224; HRMS (APCI) calcd for $C_{27}H_{23}O_2$ $(M+H)^+$ 379.16926 found 379.16989; HPLC (ODH, 0.5% isopropanol in hexane, 0.5 mL/min, 1 mg/mL, 30 min, UV 254 nm) retention times of 12.9 min (minor) and 13.9 min (major), 94% ee.



(*S*)-1-(naphthalen-1-yl)-2,2-diphenylcyclopropanecarboxylic acid (**3.44**)

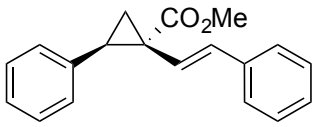
To a round-bottom flask at room temperature was added ((*S*)-methyl 1-(naphthalen-1-yl)-2,2-diphenylcyclopropanecarboxylate (**3.43**) (24.3 mmol, 9.2 g, 1.0 equiv) in dry DMSO (50 mL). $^{t-}$BuOK (72.9 mmol, 8.2 g, 3.0 equiv) was added in several portions over 50 minutes under argon. The reaction was monitored by TLC technique until the starting material was consumed completely. The reaction mixture was cooled with ice bath and acidified by saturated ammonium chloride aqueous (150 mL), followed by a slow addition of 1 N HCl (100 mL) with vigorous stirring until the pH value reached 3-4. Sticky solid precipitate was collected by filtration, washed with water (3 x 50 mL), dissolved in ethyl acetate (250 mL), washed with brine (3 x 50 mL), dried over

anhydrous $MgSO_4$, and concentrated *in vacuo*. The crude material was purified using flash column chromatography (hexanes/ethyl acetate from 10/1 to 4/1) to provide the desired product (**3.44**) as a white solid (3.59 g, 41%) and was further enriched enantioselectivity to > 99% ee by recrystallization.

Mp: 205-206 °C; $[\alpha]^{20}_D$ 317.1° (*c* = 1.85, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.35 (d, *J* = 8.0 Hz, 1H), 7.99-7.07 (m, 14H), 6.69-6.67 (m, 2H); 3.14 (br, 1H), 2.57 (br, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 177.7, 140.9, 139.6, 133.7, 133.2, 133.0, 130.8, 130.4, 128.9, 128.7, 128.5, 127.8, 127.3, 127.1, 126.2, 126.1, 125.3, 124.5, 124.1, 44.7, 44.1, 26.6; IR (neat): 3057, 2925, 1687; HRMS (APCI) calcd for $C_{26}H_{21}O_2$ $(M+H)^+$ 365.15361 found 365.15436; HPLC (ADH, 5% isopropanol in hexane, 1.0 mL/min, 1 mg/mL, 30 min, UV 254 nm) retention times of 19.8 min (minor) and 25.7 min (major), >99% ee.

General procedure for Rh_2(*R*-BTPCP)$_4$-catalyzed cyclopropanation

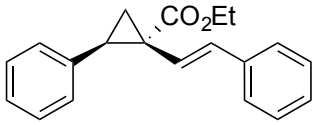
To a 25 mL flame-dried round-bottom flask, kept under a dry atmosphere of argon, was added alkene (2.0 mmol, 5.0 equiv), dry, and degassed dichloromethane (1.0 mL) and Rh_2(*R*-BTPCP)$_4$ (7.0 mg, 0.01 equiv). The given diazo compound (0.4 mmol, 1.0 equiv), dissolved in dry and degassed dichloromethane (2.0 mL), was then added to the former solution drop-wise over 1.0 hour at ambient temperature. The mixture was allowed to stir for at least 30 min after addition until the diazo compound was fully consumed upon TLC, and was then concentrated *in vacuo*. The crude residue was analyzed by ^{1}H NMR and purified by flash column chromatography (hexanes/ethyl acetate) to afford the cyclopropane.



(1*R*,2*R*)-methyl 2-phenyl-1-((*E*)-styryl)cyclopropanecarboxylate (**3.49**)

This compound was prepared by the general procedure for Rh_2(*R*-BTPCP)$_4$-catalyzed cyclopropanation. Derived from (*E*)-methyl 2-diazo-4-phenylbut-3-enoate (**3.1**) (0.4 mmol, 80.8 mg, 1.0 equiv) and styrene (**3.8**) (2.0 mmol, 208mg, 5.0 equiv). The crude residue was analyzed by ^{1}H NMR and purified by flash column chromatography (hexanes/ethyl acetate = 50/1) to afford the product (**3.49**) as a white solid (95.3 mg, 86%). The NMR spectrum is consistent with previously reported data.[8]

^{1}H NMR (400 MHz, $CDCl_3$): δ 7.25−7.21 (m, 4H), 7.19-7.13 (m, 6H), 6.35 (d, *J* = 16.2Hz, 1H), 6.14 (d, *J* = 16.2Hz, 1H), 3.77(s, 3H), 3.04-2.99 (m, 1H), 2.03 (dd, *J* = 9.2, 4.9 Hz, 1H), 1.88 (dd, *J* = 7.3, 5.2Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 174.1, 137.0, 135.5, 133.0, 129.1, 128.3, 127.9, 127.3, 126.7, 126.2, 124.0, 52.4, 34.9, 33.2, 18.6; HPLC; (OJH, 1.5% isopropanol in hexane, 1.0 mL/min, 1 mg/mL, 30 min, UV 254 nm) retention times of 15.1 min (major) and 19.9 min (minor), 91% ee.

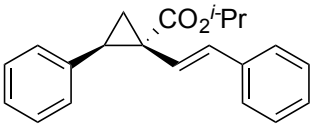


(1*R*,2*R*)-ethyl 2-phenyl-1-((*E*)-styryl)cyclopropanecarboxylate (**3.53**)

This compound was prepared by the general procedure for Rh_2(*R*-BTPCP)$_4$-catalyzed cyclopropanation. Derived from (*E*)-ethyl 2-diazo-4-phenylbut-3-enoate (**3.50**) (0.4 mmol, 86.4 mg, 1.0 equiv) and styrene (**3.8**) (2.0 mmol, 208 mg, 5.0 equiv). The crude residue was analyzed by ^{1}H NMR and purified by flash column chromatography

(hexanes/ethyl acetate = 50/1) to afford the product (**3.53**) as a white solid (102.9 mg, 88%). The NMR spectrum is consistent with previously reported data.[11]

$[\alpha]^{20}_{D:}$ 110.9° (*c* = 8.73, $CHCl_3$); ^{1}H NMR (400 MHz; $CDCl_3$) δ 7.20-7.11 (m, 10H), 6.32 (d, *J* = 15.9 Hz, 1H), 6.16 (d, *J* = 15.9 Hz, 1H), 4.20 (dtt, *J* = 10.6, 7.2, 3.7 Hz, 2H), 3.01 (dd, *J* = 9.0, 7.5 Hz, 1H), 2.01 (dd, *J* = 9.2, 5.2 Hz, 1H), 1.80 (dd, *J* = 7.2, 5.0 Hz, 1H), 1.27 (t, *J* = 7.2 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 173.5, 137.1, 135.5, 132.7, 129.0, 128.3, 127.9, 127.2, 126.6, 126.1, 124.2, 61.1, 34.9, 33.3, 18.4, 14.2; IR (film): 3027, 2980, 1716, 1244; HRMS (APCI) calcd for $C_{20}H_{21}O_2$ $(M+H)^+$ 293.15361 found 293.15338; HPLC (S,S-Whelk, 1.0% isopropanol in hexane, 0.6 mL/min, 1 mg/mL, 40 min, UV 254 nm) retention times of 19.4 min (major) and 26.9 min (minor), 93% ee.



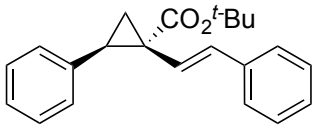
(1*R*,2*R*)-i*so*-propyl 2-phenyl-1-((*E*)-styryl)cyclopropanecarboxylate (**3.54**)

This compound was prepared by the general procedure for Rh_2(*R*-BTPCP)$_4$-catalyzed cyclopropanation. Derived from (*E*)-isopropyl 2-diazo-4-phenylbut-3-enoate (**3.51**) (0.4 mmol, 92 mg, 1.0 equiv) and styrene (**3.8**) (2.0 mmol, 208mg, 5.0 equiv). The crude residue was analyzed by ^{1}H NMR and purified by flash column chromatography (hexanes/ethyl acetate = 50/1) to afford the product (**3.54**) (109.7 mg, 89%). The NMR spectrum is consistent with previously reported data.[11]

$[\alpha]^{20}_{D:}$ 110.9° (*c* = 3.50, $CHCl_3$); ^{1}H NMR (400 MHz; $CDCl_3$) δ 7.24-7.12 (m, 10H), 6.31 (d, *J* = 15.9 Hz, 1H), 6.14 (d, *J* = 15.9 Hz, 1H), 5.09-5.06 (m, 1H), 2.98 (dd, *J* = 9.2, 7.3

[11] Davies, H. M. L.; Bruzinski, P. R.; Lake, D. H.; Kong, N.; Fall, M. J. *J. Am. Chem. Soc.* **1996**, *118*, 6897.

Hz, 1H), 2.01 (dd, *J* = 9.2, 4.9 Hz, 1H), 1.79 (dd, *J* = 7.2, 4.9 Hz, 1H), 1.28 (d, *J* = 6.4 Hz, 3H), 1.26 (d, *J* = 6.4 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 172.9, 137.3, 135.7, 132.4, 129.1, 128.3, 127.9, 127.1, 126.7, 126.2, 124.4, 68.5, 34.9, 33.5, 21.8, 18.3; IR (film): 3027, 2980, 1712, 1247; HRMS (APCI) calcd for $C_{21}H_{23}O_2$ $(M+H)^+$ 307.16926 found 307.16905; HPLC (S,S-Whelk, 1.0% isopropanol in hexane, 0.6 mL/min, 1 mg/mL, 30 min, UV 254 nm) retention times of 17.3 min (major) and 25.3 min (minor), 96% ee.

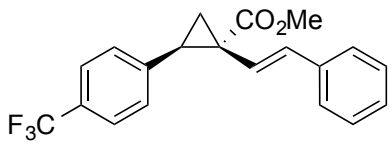


(1*R*,2*R*)-*tert*-butyl 2-phenyl-1-((*E*)-styryl)cyclopropanecarboxylate (**3.55**)

This compound was prepared by the general procedure for Rh_2(*R*-BTPCP)$_4$-catalyzed cyclopropanation. Derived from (*E*)-*tert*-butyl 2-diazo-4-phenylbut-3-enoate (**3.52**) (0.4 mmol, 97.6 mg, 1.0 equiv) and styrene (**3.8**) (2.0 mmol, 208mg, 5.0 equiv). The crude residue was analyzed by ^{1}H NMR and purified by flash column chromatography (hexanes/ethyl acetate = 50/1) to afford the product (**3.55**) (112.5 mg, 87%). The NMR spectrum is consistent with previously reported data.[11]

$[\alpha]^{20}_{D:}$ 86.2° (*c* = 1.11, $CHCl_3$); ^{1}H NMR (400 MHz; $CDCl_3$) δ 7.23-7.12 (m, 10H), 6.29 (d, *J* = 15.9 Hz, 1H), 6.13 (d, *J* = 15.9 Hz, 1H), 2.92 (dd, *J* = 8.8, 7.3 Hz, 1H), 1.95 (dd, *J* = 9.2, 5.2 Hz, 1H), 1.74 (dd, *J* = 7.3, 4.9 Hz, 1H), 1.49 (s, 9H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 172.6, 137.3, 135.9, 132.1, 129.1, 128.3, 127.9, 127.1, 126.6, 126.1, 124.8, 80.9, 68.5, 34.6, 34.1, 28.1, 18.1; IR (film): 3027, 2980, 1712, 1247; HRMS (APCI) calcd for $C_{22}H_{25}O_2$ $(M+H)^+$ 321.18491 found 321.18473; HPLC (S,S-Whelk, 1.0%

isopropanol in hexane, 0.6 mL/min, 1 mg/mL, 30 min, UV 254 nm) retention times of 11.1 min (major) and 13.3 min (minor), 95% ee.

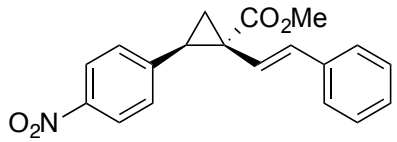


(1*R*,2*R*)-methyl 1-((*E*)-styryl)-2-(4-(trifluoromethyl)phenyl)cyclopropanecarboxylate (**3.67**)

This compound was prepared by the general procedure for Rh_2(*R*-BTPCP)$_4$-catalyzed cyclopropanation. Derived from (*E*)-methyl 2-diazo-4-phenylbut-3-enoate (**3.1**) (0.4 mmol, 80.8 mg, 1.0 equiv) and 1-(trifluoromethyl)-4-vinylbenzene (**3.56**) (2.0 mmol, 344.1 mg, 5.0 equiv). The crude residue was analyzed by ^{1}H NMR and purified by flash column chromatography (hexanes/ethyl acetate = 50/1) to afford the product (**3.67**) as a colorless oil (120.3 mg, 87%). The NMR spectrum is consistent with previously reported data.[12]

^{1}H NMR (400 MHz, $CDCl_3$): δ 7.48 (d, *J* = 8.2 Hz, 2H), 7.26-7.19 (m, 5H), 7.17-7.15 (m, 2H), 6.39 (d, *J* = 16.2 Hz, 1H), 6.11 (d, *J* = 16.2 Hz, 1H), 3.76 (s, 3H), 3.04-3.00 (m, 1H), 2.07 (dd, *J* = 8.8, 5.2 Hz, 1H), 1.85 (dd, *J* = 7.2, 5.3 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 173.7, 139.9, 133.9, 129.2, 128.5, 127.6, 126.2, 124.9, 124.8, 123.2, 52.6, 34.0, 33.8, 18.6; ^{19}F NMR (376 MHz, $CDCl_3$) δ, -62.8; HPLC (S,S-Whelk, 1.5% isopropanol in hexane, 0.7 mL/min, 1 mg/mL, 30 min, UV 254 nm) retention times of 14.7 min (major) and 22.7 min (minor), 97% ee.

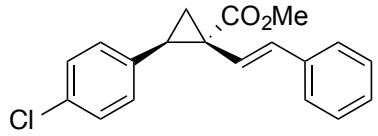
[12] Davies, H. M. L.; Panaro, S. A. *Tetrahedron* **2000**, *56*, 4871.



(1*R*,2*R*)-methyl 2-(4-nitrophenyl)-1-((*E*)-styryl)cyclopropanecarboxylate (**3.68**)

This compound was prepared by the general procedure for Rh_2(*R*-BTPCP)$_4$-catalyzed cyclopropanation. Derived from (*E*)-methyl 2-diazo-4-phenylbut-3-enoate (**3.1**) (0.4 mmol, 80.8 mg, 1.0 equiv) and 1-nitro-4-vinylbenzene (**3.57**) (2.0 mmol, 344.1 mg, 5.0 equiv). The crude residue was analyzed by ^{1}H NMR and purified by flash column chromatography (hexanes/ethyl acetate = 50/1) to afford the product (**3.68**) as a yellow oil (118.8 mg, 92%).

$[\alpha]^{20}_{D:}$ 82.8^o (*c* = 0.63, $CHCl_3$); ^{1}H NMR (400 MHz; $CDCl_3$) δ 8.08 (d, *J* = 8.8 Hz, 2H), 7.28-7.15 (m, 7H), 6.41 (d, *J* = 15.9 Hz, 1H), 6.10 (d, *J* = 16.2 Hz, 1H), 3.77 (s, 3H), 3.06 (dd, *J* = 8.7, 7.5 Hz, 1H), 2.11 (dd, *J* = 9.0, 5.3 Hz, 1H), 1.91 (dd, *J* = 7.0, 5.5 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 173.4, 146.7, 143.6, 136.2, 134.2, 129.6, 128.5, 127.8, 126.2, 123.1, 122.6, 52.7, 34.4, 33.9, 18.8; IR (film): 3025, 2923, 2853, 1722, 1518, 1344; HRMS (APCI) calcd for $C_{19}H_{18}O_4N$ $(M+H)^+$ 324.12303 found 324.12295; HPLC (ODH, 6.0% isopropanol in hexane, 1.0 mL/min, 1 mg/ml, 40 min, UV 254 nm) retention times of 13.1 min (minor) and 14.7 min (minor), 95% ee.

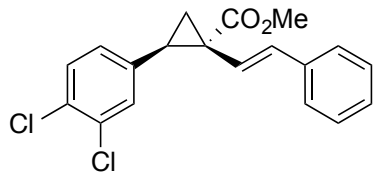


(1*R*,2*R*)-methyl 2-(4-chlorophenyl)-1-((*E*)-styryl)cyclopropanecarboxylate (***R*-3.46**)

This compound was prepared by the general procedure for Rh_2(*R*-BTPCP)$_4$-catalyzed cyclopropanation. Derived from (*E*)-methyl 2-diazo-4-phenylbut-3-enoate (**3.1**) (0.4

mmol, 80.8 mg, 1.0 equiv) and 1-chloro-4-vinylbenzene (**3.45**) (2.0 mmol, 280 mg, 5.0 equiv). The crude residue was analyzed by ^{1}H NMR and purified by flash column chromatography (hexanes/ethyl acetate = 50/1) to afford the product (***R*-3.46**) as a transparent oil (107.3 mg, 86%).

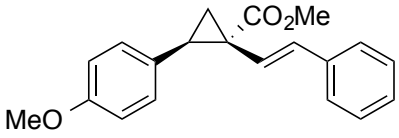
$[\alpha]^{20}_{D:}$ 63.1° (*c* = 2.67, $CHCl_3$); ^{1}H NMR (400 MHz; $CDCl_3$) δ 7.25-7.15 (m, 7H), 7.05-7.03 (m, 2H), 6.34 (d, *J* = 15.9 Hz, 1H), 6.12 (d, *J* = 15.9 Hz, 1H), 3.74 (s, 3H), 2.95 (dd, *J* = 9.0, 7.5 Hz, 1H), 2.01 (dd, *J* = 9.2, 7.2 Hz, 1H), 1.77 (dd, *J* = 7.3, 5.2 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 173.8, 136.7, 134.1, 133.4, 132.5, 130.3, 128.4, 128.1, 127.5, 126.2, 123.5, 52.4, 34.1, 33.4, 18.5; IR (film): 3026, 2950, 1719, 1459, 1248; HRMS (APCI) calcd for $C_{19}H_{18}O_2Cl$ $(M+H)^+$ 313.09898 found 313.09881; HPLC (S,S-Whelk, 1.5% isopropanol in hexane, 0.7 mL/min, 1 mg/mL, 30 min, UV 254 nm) retention times of 17.1 min (major) and 24.2 min (minor), 95% ee.



(1*R*,2*R*)-methyl 2-(3,4-dichlorophenyl)-1-((E)-styryl)cyclopropanecarboxylate (**3.69**)

This compound was prepared by the general procedure for Rh_2(*R*-BTPCP)$_4$-catalyzed cyclopropanation. Derived from (*E*)-methyl 2-diazo-4-phenylbut-3-enoate (**3.1**) (0.4 mmol, 80.8 mg, 1.0 equiv) and 1,2-dichloro-4-vinylbenzene (**3.58**) (2.0 mmol, 344 mg, 5.0 equiv). The crude residue was analyzed by ^{1}H NMR and purified by flash column chromatography (hexanes/ethyl acetate = 50/1) to afford the product (**3.69**) as a transparent oil (121.8 mg, 88%).

$[\alpha]^{20}_{D:}$ 81.5° (*c* = 0.97, $CHCl_3$); ^1H NMR (400 MHz; $CDCl_3$) δ 7.27-7.18 (m, 7H), 6.91 (dd, *J* = 8.2, 2.1 Hz, 1H), 6.37 (d, *J* = 15.9 Hz, 1H), 6.12 (d, *J* = 15.9 Hz, 1H), 3.75 (s, 3H), 2.92 (dd, *J* = 9.2, 7.3 Hz, 1H), 2.04-2.00 (m, 1H), 1.77 (dd, *J* = 7.2, 5.3 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 173.6, 136.5, 136.0, 133.8, 132.0, 131.1, 130.7, 129.8, 128.5, 128.1, 127.6, 126.2, 123.0, 52.6, 33.5, 18.4; IR (film): 3025, 2950, 1719, 1434, 1246; HRMS (APCI) calcd for $C_{19}H_{17}O_2Cl_2$ $(M+H)^+$ 347.06001 found 347.05983; HPLC (S,S-Whelk, 1.5% isopropanol in hexane, 0.7 mL/min, 1 mg/mL, 30 min, UV 254 nm) retention times of 17.7 min (major) and 26.1 min (minor), 93% ee.

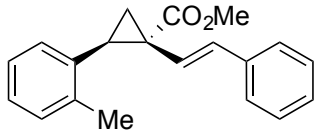


(1*R*,2*R*)-methyl 2-(4-methoxyphenyl)-1-((*E*)-styryl)cyclopropanecarboxylate (**3.70**)

This compound was prepared by the general procedure for Rh_2(*R*-BTPCP)$_4$-catalyzed cyclopropanation. Derived from (*E*)-methyl 2-diazo-4-phenylbut-3-enoate (**3.1**) (0.4 mmol, 80.8 mg, 1.0 equiv) and 1-methoxy-4-vinylbenzene (**3.59**) (2.0 mmol, 268 mg, 5.0 equiv). The crude residue was analyzed by ^1H NMR and purified by flash column chromatography (hexanes/ethyl acetate = 50/1) to afford the product (**3.70**) as a transparent oil (120.8 mg, 94%). The NMR spectrum is consistent with previously reported data.[11]

^1H NMR (400 MHz, $CDCl_3$): δ 7.22-7.12 (m, 5H), 7.03 (d, *J* = 8.5 Hz, 2H), 6.32 (d, *J* = 16.0 Hz, 1H), 6.15 (d, *J* = 16.0 Hz, 1H), 3.73 (s, 3H), 3.69 (s, 3H), 2.95 (t, *J* = 8.5 Hz, 1H), 1.99 (dd, *J* = 9.2, 4.9 Hz, 1H), 1.75 (dd, *J* = 7.3, 5.2 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 174.1, 158.3, 137.0, 132.7, 130.0, 128.3, 127.4, 127.2, 126.1, 124.1, 113.3,

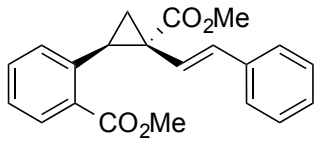
55.0, 52.3, 34.5, 33.1, 18.6. HPLC: (S,S-Whelk, 1.5% isopropanol in hexane, 0.7 mL/min, 1 mg/mL, 30 min, UV 254 nm) retention times of 28.9 min (major) and 36.5 min (minor), 84% ee.



(1*R*,2*R*)-methyl 1-((*E*)-styryl)-2-(o-tolyl)cyclopropanecarboxylate (**3.71**)

This compound was prepared by the general procedure for Rh_2(*R*-BTPCP)$_4$-catalyzed cyclopropanation. Derived from (*E*)-methyl 2-diazo-4-phenylbut-3-enoate (**3.1**) (0.4 mmol, 80.8 mg, 1.0 equiv) and 1-methyl-2-vinylbenzene (**3.60**) (2.0 mmol, 236 mg, 5.0 equiv). The crude residue was analyzed by ^{1}H NMR and purified by flash column chromatography (hexanes/ethyl acetate = 50/1) to afford the product (**3.71**) as a colorless oil (103.1 mg, 88%).

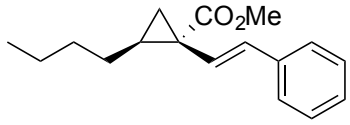
$[\alpha]^{20}_{D:}$ 43.4^o (*c* = 3.80, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.17-7.00 (m, 9H), 6.16 (d, *J* = 16.0 Hz, 1H), 6.10 (d, *J* = 16.0 Hz, 1H), 3.78 (s, 3H), 3.69 (s, 3H), 2.93 (t, *J* = 8.4 Hz, 1H), 3.26 (s, 3H), 2.05 (dd, *J* = 9.0, 5.0 Hz, 1H), 1.86 (dd, *J* = 7.5, 5.0 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 174.5, 138.9, 137.5, 134.3, 131.4, 129.9, 128.6, 127.4, 127.3, 126.3, 125.8, 123.8, 52.7, 35.2, 32.1, 19.9, 19.1; IR (film): 3024, 2950, 1718, 1434, 1244; HRMS (APCI) calcd for $C_{20}H_{21}O_2$ $(M+H)^+$ 293.15415 found 293.15375; HPLC: (OJH, 1.5% isopropanol in hexane, 1.0 mL/min, 1 mg/mL, 30 min, UV 254 nm) retention times of 12.9 min (minor) and 15.5 min (major), 93% ee.



methyl 2-((1*R*,2*R*)-2-(methoxycarbonyl)-2-((*E*)-styryl)cyclopropyl)benzoate (**3.72**)

This compound was prepared by the general procedure for Rh_2(*R*-BTPCP)$_4$-catalyzed cyclopropanation. Derived from (*E*)-methyl 2-diazo-4-phenylbut-3-enoate (**3.1**) (0.4 mmol, 80.8 mg, 1.0 equiv) and methyl 2-vinylbenzoate (**3.61**) (2.0 mmol, 324 mg, 5.0 equiv). The crude residue was analyzed by ^{1}H NMR and purified by flash column chromatography (hexanes/ethyl acetate = 50/1) to afford the product (**3.72**) as a colorless oil (78.7 mg, 59%).

$[\alpha]^{20}_{D:}$ 1.3^o (*c* = 2.56, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.21-7.01 (m, 9H), 6.19 (s, 2H), 7.01-6.99 (m, 3H), 3.75 (s, 3H), 2.86 (t, *J* = 8.8 Hz, 1H), 2.28 (s, 3H), 1.98 (dd, *J* = 9.2, 4.9 Hz, 1H), 1.83 (dd, *J* = 7.3, 4.9 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 174.0, 168.9, 150.9, 136.9, 132.1, 129.3, 128.3, 128.1, 127.2, 126.2, 125.6, 123.6, 121.8, 52.4, 32.3, 30.6, 20.7, 17.3; IR (film): 3025, 2951, 1762, 1718, 1449; HRMS (APCI) calcd for $C_{21}H_{21}O_4$ $(M+H)^+$ 337.14398 found 337.14349; HPLC (ADH, 5% isopropanol in hexane, 0.8 mL/min, 1 mg/ml, 30 min, UV 254 nm) retention times of 11.4 min (minor) and 13.6 min (major), 89% ee.

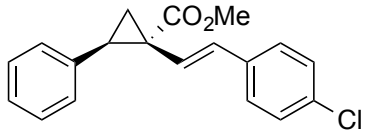


(1*S*,2*S*)-methyl 2-butyl-1-((*E*)-styryl)cyclopropanecarboxylate (**3.73**)

This compound was prepared by the general procedure for Rh_2(*R*-BTPCP)$_4$-catalyzed cyclopropanation. Derived from (*E*)-methyl 2-diazo-4-phenylbut-3-enoate (**3.1**) (0.4

mmol, 80.8 mg, 1.0 equiv) and hex-1-ene (**3.62**) (2.0 mmol, 168 mg, 5.0 equiv). The crude residue was analyzed by ^{1}H NMR and purified by flash column chromatography (hexanes/ethyl acetate = 100/1) to afford the product (**3.73**) as a colorless oil (65 mg, 60%).

$[\alpha]^{20}_{D:}$ 2.7° (*c* = 2.04, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.41-7.39 (m, 2H), 7.34-7.29(m, 2H), 7.26-7.21(m, 1H), 6.65 (d, *J* = 16.1Hz, 1H), 6.33 (d, *J* = 15.9 Hz, 1H), 3.69 (s, 3H), 1.68-1.64 (m, 1H), 1.61-1.58 (m, 1H), 1.37-1.25 (m, 6H), 1.12 (dd, *J* = 6.6, 4.1 Hz, 1H), 0.85 (t, *J* = 6.8 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 174.9, 137.0, 131.6, 128.5, 127.3, 126.2, 124.6, 52.1, 31.7, 31.6, 30.5, 27.8, 22.3, 19.3, 14.0; IR (film): 2953, 2927, 2856, 1720, 1242; HRMS (APCI) calcd for $C_{17}H_{23}O_2$ $(M+H)^+$ 259.16980 found 259.16931; HPLC: (S,S-Whelk, 1.5% isopropanol in hexane, 0.7 mL/min, 1 mg/mL, 30 min, UV 254 nm) retention times of 10.9 min (major) and 16.9 min (minor), 90% ee.

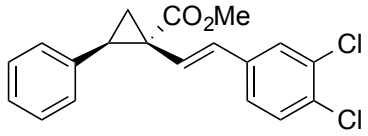


(1*R*,2*R*)-methyl 1-((*E*)-4-chlorostyryl)-2-phenylcyclopropanecarboxylate (**3.74**)

This compound was prepared by general procedure for Rh_2(*R*-BTPCP)$_4$-catalyzed cyclopropanation. Derived from (*E*)-methyl 4-(4-chlorophenyl)-2-diazobut-3-enoate (**3.63**) (0.4 mmol, 94.4 mg, 1.0 equiv) and styrene (**3.8**) (2.0 mmol, 208 mg, 5.0 equiv). The crude residue was analyzed by ^{1}H NMR and purified by flash column chromatography (hexanes/ethyl acetate = 20/1) to afford the product (**3.74**) as a colorless oil (91.3 mg, 82%).

$[\alpha]^{20}_{D:}$ 125.6° (*c* = 1.69, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.25−7.21 (m, 4H), 7.19-7.13 (m, 6H), 6.35 (d, *J* = 16.2Hz, 1H), 6.14 (d, *J* = 16.2Hz, 1H), 3.77(s, 3H), 3.04-2.99

(m, 1H), 2.03 3 (dd, J = 9.2, 4.9 Hz, 1H), 1.88 (dd, J = 7.3, 5.2Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 173.9, 135.5, 135.3, 132.9, 131.6, 129.1, 128.5, 127.9, 127.4, 126.8, 124.8, 52.5, 35.1, 33.1, 18.6; IR (film): 3029, 2950, 1720, 1246; HRMS (APCI) calcd for $C_{19}H_{18}ClO_2$ $(M+H)^+$ 313.09953 found 313.09889; HPLC: (S,S-Whelk, 1.5% isopropanol in hexane, 1.0 mL/min, 1 mg/mL, 30 min, UV 254 nm) retention times of 10.8 min (major) and 13.5 min (minor), 90% ee.

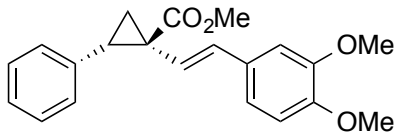


(1*R*,2*R*)-methyl 1-((*E*)-3,4-dichlorostyryl)-2-phenylcyclopropanecarboxylate (**3.75**)

This compound was prepared by the general procedure for Rh_2(*R*-BTPCP)$_4$-catalyzed cyclopropanation. Derived from (*E*)-methyl 2-diazo-4-(3,4-dichlorophenyl)but-3-enoate (**3.64**) (0.4 mmol, 108 mg, 1.0 equiv) and styrene (**3.8**) (2.0 mmol, 208 mg, 5.0 equiv). The crude residue was analyzed by ^{1}H NMR and purified by flash column chromatography (hexanes/ethyl acetate = 20/1) to afford the product (**3.75**) as a colorless oil (109 mg, 79%).

$[\alpha]^{20}_{D:}$ 62.8^o (*c* = 2.95, $CHCl_3$); ^{1}H NMR (400 MHz; $CDCl_3$) δ 7.24-7.21 (m, 5H), 7.11-7.09 (m, 2H), 6.91 (dd, J = 8.2, 2.1 Hz, 1H), 6.16 (d, J = 0.9 Hz, 1H), 3.76 (s, 3H), 3.06 (dd, J = 8.8, 7.6 Hz, 1H), 2.03 (dd, J = 9.2, 5.2 Hz, 1H), 1.80 (dd, J = 7.3, 5.2 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 173.6, 137.0, 135.1, 132.4, 130.8, 130.2, 129.1, 128.0, 127.8, 126.9, 126.2, 125.3, 52.5, 35.4, 32.9, 18.6; IR (film): 3027, 2950, 1718, 1241; HRMS (APCI) calcd for $C_{19}H_{17}O_2Cl_2$ $(M+H)^+$ 347.06001 found 347.05982; HPLC (S,S-

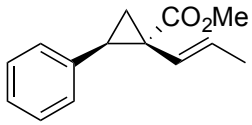
Whelk, 1.5% isopropanol in hexane, 1.0 mL/min, 1 mg/mL, 30 min, UV 254 nm) retention times of 10.8 min (major) and 12.4 min (minor), 86% ee.



(1*R*,2*S*)-methyl 1-(3,4-dimethoxyphenethyl)-2-phenylcyclopropanecarboxylate (**3.76**)

This compound was prepared by the general procedure for Rh_2(*R*-BTPCP)$_4$-catalyzed cyclopropanation. Derived from (*E*)-methyl 2-diazo-4-(3,4-dichlorophenyl)but-3-enoate (**3.65**) (0.4 mmol, 108 mg, 1.0 equiv) and styrene (**3.8**) (2.0 mmol, 208 mg, 5.0 equiv), Rh_2(*S*-BTPCP)$_4$ was used. The crude residue was analyzed by ^{1}H NMR and purified by flash column chromatography (hexanes/ethyl acetate = 20/1) to afford the product (**3.76**) as a yellow oil (94.6 mg, 70%).

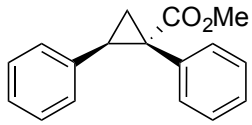
$[\alpha]^{20}_{D:}$ –90.5^o (*c* = 5.60, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.25−7.21 (m, 2H), 7.19-7.13 (m, 3H), 6.75-6.65 (m, 3H), 6.31 (d, *J* = 15.9 Hz, 1H), 5.97 (d, *J* = 15.9 Hz, 1H), 3.85(s, 3H), 3.81 (s, 3H), 3.77 (s, 3H), 3.01-2.98 (m, 1H), 2.02 (dd, *J* = 9.0, 5.0 Hz, 1H), 1.82 (dd, *J* = 7.3, 5.2Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 174.2, 148.8, 148.6, 135.6, 132.9, 130.2, 129.0, 127.9, 126.6, 122.2, 119.2, 110/9, 108.8, 55.8, 55.7, 52.4, 34.7, 33.2, 18.6; IR (film): 2950, 1716, 1512, 1453, 1246; HRMS (APCI) calcd for $C_{21}H_{22}NaO_4$ $(M+Na)^+$ 361.14158 found 361.14133; HPLC: (ODH, 6% isopropanol in hexane, 1.0 mL/min, 1 mg/mL, 30 min, UV 254 nm) retention times of 12.5 min (major) and 14.2 min (minor), 94% ee.



(1*R*,2*R*)-methyl 2-phenyl-1-((*E*)-prop-1-en-1-yl)cyclopropanecarboxylate (**3.77**)

This compound was prepared by the general procedure for Rh_2(*R*-BTPCP)$_4$-catalyzed cyclopropanation. Derived from methyl (*E*)-2-diazopent-3-enoate (**3.66**) (0.4 mmol, 56 mg, 1.0 equiv) and styrene (**3.8**) (2.0 mmol, 208 mg, 5.0 equiv) catalyzed by Rh_2(*S*-BTPCP)$_4$. The crude residue was analyzed by ^{1}H NMR and purified by flash column chromatography (hexanes/ethyl acetate = 20/1) to afford the product (**3.77**) as a colorless oil (14.9 mg, 17%).

$[\alpha]^{20}_{D:}$ 27.3° (*c* = 0.48, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.25−7.19 (m, 3H), 7.08 (d, *J* = 6.7 Hz, 3H),5.45-5.37 (m, 2H), 3.74 (s, 3H), 2.89-2.84 (m, 2H), 1.86 (dd, *J* = 9.2, 4.9 Hz, 1H), 1.66 (dd, *J* = 7.2, 5.0 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 174.5, 135.9, 129.3, 129.1, 127.8, 126.5, 124.3, 52.3, 33.9, 33.2, 17.8, 17.7; IR (film): 3029, 2950, 1720, 1255; HRMS (APCI) calcd for $C_{14}H_{17}O_2$ $(M+H)^+$ 217.12285 found 217.12225; HPLC: (S,S-Whelk, 0.5% isopropanol in hexane, 0.5 mL/min, 1 mg/mL, 30 min, UV 254 nm) retention times of 12.7 min (major) and 13.9 min (minor), 46% ee.

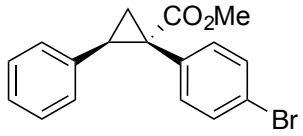


(1*S*,2*R*)-methyl 1,2-diphenylcyclopropanecarboxylate (***R*-3.13**)

This compound was prepared by the general procedure for Rh_2(*R*-BTPCP)$_4$-catalyzed cyclopropanation. Derived from methyl 2-diazo-2-phenylacetate (**3.5**) (0.4 mmol, 70.5 mg, 1.0 equiv) and styrene (**3.8**) (2.0 mmol, 208 mg, 5.0 equiv). The crude residue was

analyzed by ^{1}H NMR and purified by flash column chromatography (hexanes/ethyl acetate = 50/1) to afford the product (***R*-3.13**) as a white foam (80.6 mg, 80%). The NMR spectrum is consistent with previously reported data.[8]

^{1}H NMR (400 MHz, $CDCl_3$): δ 7.17−7.15 (m, 3H), 7.09-7.05 (m, 5H), 6.81-6.79 (m, 2H), 3.69 (s, 3H), 3.15 (dd, *J* = 9.4, 7.4 Hz, 1H), 2.18 (dd, *J* = 9.4, 5.1 Hz, 1H), 1.92 (dd, *J* = 7.2, 4.9 Hz, 1H); HPLC (S,S-WHELK, 1.5% isopropanol in hexane, 0.7 mL/min, 1 mg/mL, 30 min, UV 254 nm) retention times of 12.9 min (major) and 15.5 min (minor), 83% ee.

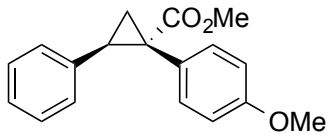


(1*S*,2*R*)-methyl 1-(4-bromophenyl)-2-phenylcyclopropanecarboxylate (**3.80**)

This compound was prepared by the general procedure for Rh_2(*R*-BTPCP)$_4$-catalyzed cyclopropanation. Derived from methyl 2-(4-bromophenyl)-2-diazoacetate (**3.17**) (0.4 mmol, 101.6 mg, 1.0 equiv) and styrene (**3.8**) (2.0 mmol, 208mg, 5.0 equiv). The crude residue was analyzed by ^{1}H NMR and purified by flash column chromatography (hexanes/ethyl acetate = 50/1) to afford the product (**3.80**) as a white solid (104.9 mg, 80%). The NMR spectrum is consistent with previously reported data.[4]

^{1}H NMR (400 MHz, $CDCl_3$): δ 7.25-7.23 (m, 2H), 7.09-7.06 (m, 3H), 6.90-6.87 (m, 2 H), 6.78-6.75 (m, 2H), 3.65 (s, 3H), 3.11 (dd, J = 9.2, 7.3 Hz, 1H), 2.13 (dd, J = 9.2, 4.9 Hz, 1H), 1.83 (dd, J = 7.3, 4.9 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 173.7, 135.8, 133.9, 133.5, 130.8, 127.9, 127.8, 126.5, 121.1, 52.6, 36.7, 33.1, 20.3; HPLC; (SS-WHELK,

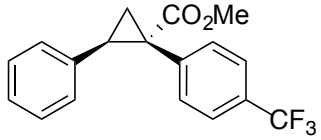
2.0% isopropanol in hexane, 1.0 mL/min, 1 mg/mL, 30 min, UV 254 nm) retention times of 11.3 min (major) and 14.9 min (minor), 85% ee.



(1*S*,2*R*)-methyl 1-(4-methoxyphenyl)-2-phenylcyclopropanecarboxylate (**3.81**)

This compound was prepared by the general procedure for Rh_2(*R*-BTPCP)$_4$-catalyzed cyclopropanation. Derived from methyl 2-diazo-2-(4-methoxyphenyl)acetate (**3.78**) (0.4 mmol, 82.4 mg, 1.0 equiv) and styrene (**3.8**) (2.0 mmol, 208mg, 5.0 equiv). The crude residue was analyzed by ^{1}H NMR and purified by flash column chromatography (hexane/ethyl acetate = 50/1) to afford the product (**3.81**) as a colorless oil (83.5 mg, 74%). The NMR spectrum is consistent with previously reported data.[13]

^{1}H NMR (400 MHz, $CDCl_3$): δ 7.09-7.07 (m, 3H), 6.99-6.95 (m, 2H), 6.81-6.78 (m, 2 H), 6.69-6.68 (m, 2H), 3.74 (s, 3H), 3.68 (s, 3H), 3.10 (dd, *J* = 9.4, 7.4 Hz, 1H), 2.15 (dd, *J* = 9.4, 4.7 Hz, 1H), 1.85 (dd, *J* = 7.2, 4.9 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 174.6, 158.4, 136.4, 132.8, 128.0, 127.6, 126.7, 126.2, 113.1, 54.9, 52.5, 36.6, 33.1, 20.7; HPLC; (ODH, 0.7% isopropanol in hexane, 1.0 mL/min, 1 mg/mL, 30 min, UV 254 nm) retention times of 9.1 min (major) and 12.0 min (minor), 91% ee.

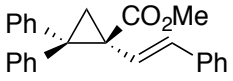


(1*S*,2*R*)-methyl 2-phenyl-1-(4-(trifluoromethyl)phenyl)cyclopropanecarboxylate (**3.82**)

[13] Nagashima, T.; Davies, H. M. L. *Org. Lett*. **2002**, *4*, 1989.

This compound was prepared by the general procedure for Rh_2(*R*-BTPCP)$_4$-catalyzed cyclopropanation. Derived from methyl 2-diazo-2-(4-(trifluoromethyl)phenyl)acetate (**3.79**) (0.4 mmol, 97.6 mg, 1.0 equiv) and styrene **12** (2.0 mmol, 208mg, 5.0 equiv). The crude residue was analyzed by ^{1}H NMR and purified by flash column chromatography (hexanes/ethyl acetate = 50/1) to afford the (**3.82**) as a colorless oil (109.7 mg, 86%). The NMR spectrum is consistent with previously reported data.[4]

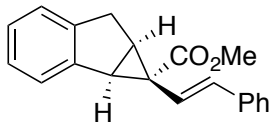
^{1}H NMR (400 MHz, $CDCl_3$): δ 7.40 (d, *J* = 8.2 Hz, 2H), 7.16 (d, *J* = 8.2 Hz, 2H), 7.10-7.08 (m, 3 H), 6.79 (dd, *J* = 6.7, 3.1 Hz, 2H), 3.69 (s, 3H), 3.19 (dd, *J* = 9.3, 7.5 Hz, 1H), 2.21 (dd, *J* = 9.3, 5.0 Hz, 1H), 1.93 (dd, *J* = 7.3, 5.2 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 173.4, 138.9, 135.5, 132.2, 127.9, 126.6, 124.6, 52.7, 36.9, 33.2, 20.1; HPLC; (ODH, 0.5% isopropanol in hexane, 1.0 mL/min, 1 mg/mL, 30 min, UV 254 nm) retention times of 6.2 min (minor) and 7.5 min (major), 89% ee.



(*S*,*E*)-methyl 2,2-diphenyl-1-styrylcyclopropanecarboxylate (**3.83**)

This compound was prepared by the general procedure for Rh_2(*R*-BTPCP)$_4$-catalyzed cyclopropanation. Derived from methyl (*E*)-2-diazo-4-phenylbut-3-enoate (**3.1**) (0.4 mmol, 80.8 mg, 1.0 equiv) and 1,1-diphenylethylene (**3.6**) (2.0 mmol, 360 mg, 5.0 equiv) and Rh_2(*S*-BTPCP)$_4$ was used. The crude residue was analyzed by ^{1}H NMR and purified by flash column chromatography (hexanes/ethyl acetate = 50/1) to afford the product (**3.83**) as a colorless oil (84.9 mg, 60%). The NMR spectrum is consistent with previously reported data.[4]

^{1}H NMR (400 MHz, $CDCl_3$): δ 7.47−7.40 (m, 4H), 7.25-7.20 (m, 6H), 7.18-7.09 (m, 5H), 6.47 (d, *J* = 16.2 Hz, 1H), 6.19 (d, *J* = 16.2 Hz, 1H), 3.40 (s, 3H), 2.63 (d, *J* = 5.5 Hz, 1H), 2.06 (d, *J* = 5.2 Hz, 1H); HPLC: (OJH, 1.5% isopropanol in hexane, 1.0 mL/min, 1 mg/mL, 50 min, UV 254 nm) retention times of 21.2 min (minor) and 31.2 min (major), 85% ee.

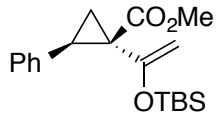


(1*S*,1a*R*,6a*R*)-methyl 1-((*E*)-styryl)-1,1a,6,6a-tetrahydrocyclopropa[a]indene-1-carboxylate (**3.85**)

This compound was prepared by the general procedure for Rh_2(*R*-BTPCP)$_4$-catalyzed cyclopropanation. Derived from methyl (*E*)-2-diazo-4-phenylbut-3-enoate (**3.1**) (0.4 mmol, 80.8 mg, 1.0 equiv) and indene (**3.84**) (2.0 mmol, 232 mg, 5.0 equiv). The crude residue was analyzed by ^{1}H NMR and purified by flash column chromatography (hexanes/ethyl acetate = 20/1) to afford the product (**3.85**) as a colorless oil (84.1 mg, 72%).

$[\alpha]^{20}_{D:}$ 42.1° (*c* = 3.32, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.37 (d, *J* = 7.3 Hz, 1H), 7.17-7.08 (m, 5H), 7.01-6.99 (m, 3H), 6.28 (d, *J* = 16.2 Hz, 1H), 5.50 (d, *J* = 16.2 Hz, 1H), 3.70 (s, 3H), 3.29 (d, *J* = 6.7 Hz, 1H), 3.23 (dd, *J* = 18.0, 6.7 Hz, 1H), 2.85 (d, *J* = 17.7 Hz, 1H), 2.71 (t, *J* = 6.6 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 173.6, 143.5, 140.8, 137.1, 136.8, 128.2, 127.2, 126.7, 126.3, 125.9, 124.8, 124.3, 119.5, 52.3, 40.4, 33.7, 32.7, 32.6; IR (film): 3024, 2949, 1717, 1448; HRMS (APCI) calcd for $C_{20}H_{19}O_2$ $(M+H)^+$ 291.13850 found 291.13805; HPLC: (S,S-Whelk, 1.5% isopropanol in hexane,

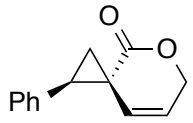
0.7 mL/min, 1 mg/mL, 30 min, UV 254 nm) retention times of 19.6 min (minor) and 27.3 min (major), 55% ee. Note: when the reaction was conducted at – 40 ^{o}C, the product was obtained in 71% yield and 56% ee.



(1*S*,2*R*)-methyl 1-(1-((*tert*-butyldimethylsilyl)oxy)vinyl)-2-phenylcyclopropanecarboxylate (**3.87**)

This compound was prepared by the general procedure for Rh_2(*R*-BTPCP)$_4$-catalyzed cyclopropanation. Derived from methyl 3-((*tert*-butyldimethylsilyl)oxy)-2-diazobut-3-enoate (**3.86**) (0.4 mmol, 102.4 mg, 1.0 equiv) and styrene (**3.8**) (2.0 mmol, 208 mg, 5.0 equiv). The crude residue was analyzed by ^{1}H NMR and purified by flash column chromatography (hexanes/ethyl acetate = 20/1) to afford the product (**3.87**) as a colorless oil (71.7 mg, 54%). The NMR spectrum is consistent with previously reported data.[14]

^{1}H NMR (400 MHz, $CDCl_3$): δ 7.22−7.18 (m, 5H), 4.19 (d, *J* = 1.2 Hz, 1H), 4.09 (d, *J* = 1.2 Hz, 1H), 3.74 (s, 1H), 2.98 (t, *J* = 8.2 Hz, 1H), 1.73 (m, 2H), 0.73 (s, 9H), 0.05 (s, 3H), -0.24 (s, 3H); HPLC: (ODH, 0% isopropanol in hexane, 0.4 mL/min, 1 mg/mL, 60 min, UV 254 nm) retention times of 27.7 min (major) and 40.5 min (minor), 23% ee.

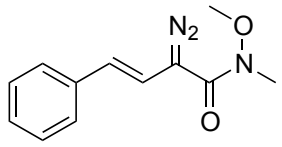


(1*R*,3*R*)-1-phenyl-5-oxaspiro[2.5]oct-7-en-4-one (**3.90**)

[14] Müller, P.; Bernardinelli, G.; Allenbach, Y. F.; Ferri, M.; Flack, H. D. *Org. Lett*. **2004**, *6*, 1725.

This compound was prepared by the general procedure for Rh_2(*R*-BTPCP)$_4$-catalyzed cyclopropanation. Derived from 3-diazo-3,6-dihydro-2H-pyran-2-one (**3.89**) (0.4 mmol, 49.6 mg, 1.0 equiv) and styrene (**3.8**) (2.0 mmol, 208 mg, 5.0 equiv). The crude residue was analyzed by ^{1}H NMR and purified by flash column chromatography (hexanes/ethyl acetate = 20/1) to afford the product (**3.90**) as a white solid (33.6 mg, 42%).

Mp: 80-82 ^{o}C; $[\alpha]^{20}_{D:}$ -17.4^o (*c* = 0.29, $CHCl_3$); ^{1}H NMR (400 MHz; $CDCl_3$) δ 7.35-7.20 (m, 5H), 5.72 (dt, *J* = 10.2, 2.8 Hz, 1H), 5.02-5.01 (m, 2H), 6.96 (dt, *J* = 10.1, 1.9 Hz, 1H), 3.25 (t, *J* = 8.4 Hz, 1H), 2.14 (dd, *J* = 9.2, 4.9 Hz, 1H), 1.56 (dd, *J* = 7.6, 4.9 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 171.9, 135.5, 129.1, 128.5, 127.2, 124.8, 121.2, 69.2, 35.2, 26.8, 22.7; IR (film): 3028, 1723, 1149; HRMS (APCI) calcd for $C_{13}H_{13}O_2$ $(M+H)^+$ 201.09155 found 201.09096; HPLC (Chiralcel ODH, 1% isopropanol in hexane, 1.0 mL/min, 1 mg/mL, 30 min, UV 254 nm) retention times of 22.5 min (minor) and 24.5 min (najor), 10% ee.

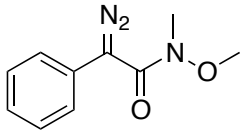


(*E*)-2-diazo-*N*-methoxy-*N*-methyl-4-phenylbut-3-enamide (**3.91**)

To a stirred solution of (*E*)-*N*-methoxy-*N*-methyl-4-phenylbut-3-enamide (3.7 g, 14.8 mmol, 1.0 equiv) and *p*-acetamidobenzenesulfonyl azide (*p*-ABSA) (7.1 g, 29.6 mmol, 2.0 equiv) in acetonitrile (100 mL) under argon atmosphere, 1,8-diazabicycloundec-7-ene (DBU) (6.6 mL, 44.4 mmol, 3.0 equiv) was added drop-wise at 0 °C. The reaction mixture was then stirred overnight. Then, saturated aqueous ammonium chloride (30 mL) was added. The crude mixture was extracted with pentane (3 x 60 mL), washed by brine

(3 x 10 mL), dried over anhydrous $MgSO_4$, concentrated *in vacuo*, and chromatographed (pentane/diethyl ether = 50/1) to afford the (*E*)-2-diazo-*N*-methoxy-*N*-methyl-4-phenylbut-3-enamide (**3.91**) (1.6 g, 47%) as a red-orange oil.

^{1}H NMR (400 MHz, $CDCl_3$): δ 7.38 (d, *J* = 7.6 Hz, 2H), 7.31 (t, *J* = 7.2 Hz, 2H), 7.19 (t, *J* = 8.0 Hz, 1H), 6.80 (d, *J* = 16.0 Hz, 1H), 5.99 (d, *J* = 16.0 Hz, 1H), 3.71 (s, 3H), 3.28 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 165.2, 136.9, 128.6, 126.8, 125.9, 121.6, 113.6, 61.4, 34.3; IR (neat): 2935, 2072, 1636, 1619, 1448, 1407, 1378, 1203; HRMS (FTMS+p-NSI) calcd for $C_{12}H_{14}O_2N_3$ $(M+H)^+$ 232.10805 found 232.10796.

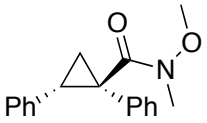


2-diazo-*N*-methoxy-*N*-methyl-2-phenylacetamide (**3.93**)

A 250 mL three-necked flask equipped with a magnetic stir bar, was charged *N*-methoxy-*N*-methyl-2-phenylacetamide (3.58 g, 20 mmol) in dry acetonitrile (100 mL) and cooled to 0 °C with ice bath under argon. Then *p*-ABSA (14.4 g, 60 mmol, 3.0 equiv) was added in one portion, followed by addition DBU drop-wise (15 mL, 100 mmol, 5 equiv) in 1 hour. Then, the ice bath was removed and the mixture was stirred at room temperature for two days. The reaction mixture was then concentrated under vacuum. To the residue, was slowly added saturated aqueous ammonium chloride (100 mL) with vigorous magnetic stirring, and the resulting mixture was extracted with diethyl ether (4 x 100 mL), the combined ether solution was washed with brine (3 x 50 mL), dried over anhydrous $MgSO_4$, and concentrated under vacuum. The crude material was purified by flash

chromatography (hexanes/diethyl ether = 15/1) to afford the desired product (**3.93**) (632 mg, 15%).

^{1}H NMR (400 MHz, $CDCl_3$) δ 7.48-7.39 (m, 2H), 7.31-7.36 (m, 2H), 7.22-7.18 (m, 1H), 3.69 (s, 3H), 3.28 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 166.5, 128.7, 127.2, 125.9, 125.5, 61.1, 34.0; IR (neat): 2936, 2072, 1632, 1358; HRMS (APCI) calcd for $C_{10}H_{12}NO_2$ $(M\text{-}N_2+H)^+$ 178.08626 found 178.08650.



(1*R*,2*S*)-*N*-methoxy-*N*-methyl-1,2-diphenylcyclopropanecarboxamide (**3.94**)

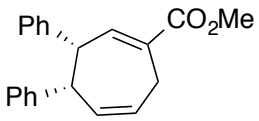
To a flame-dried round bottom flask kept under a dry atmosphere of argon, was added Rh_2(*R*-NPCP)$_4$ (0.01 equiv, 6.6 mg), styrene (**3.8**) (416 mg, 10 equiv), and dry degassed dichloromethane (1.0 mL) at room temperature. A solution of 2-diazo-*N*-methoxy-*N*-methyl-2-phenylacetamide (**3.93**) (0.4 mmol, 82 mg, 1.0 equiv) in dry, degassed dichloromethane (2.0 mL) was then added to the former solution drop-wise over 2 hours under argon atmosphere. The mixture was then allowed to stir for overnight, and concentrated *in vacuo*. The crude residue was analyzed by ^{1}H NMR and purified by flash column chromatography (hexanes/ethyl acetate = 30/1) to provide the product (**3.94**) (51.1 mg, 45%).

^{1}H NMR (400 MHz, $CDCl_3$) δ 7.10 (d, *J* = 4.8 Hz, 4H), 7.07-7.00 (m, 4H), 6.95-6.93 (m, 2H), 3.27 (dd, *J* = 7.2, 9.2 Hz, 1H), 3.15 (s, 3H), 3.13 (br, 3H), 3.00 (dd, *J* = 5.4, 6.8 Hz, 1H), 1.65 (dd, *J* = 5.4, 9.2 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 166.6, 136.8, 135.9, 129.7, 128.4, 127.7, 127.5, 126.4, 125.8, 59.9, 38.2, 33.7, 28.6, 16.2; IR (neat): 3027,

2924, 1651; HRMS (APCI) calcd for $C_{18}H_{20}NO_2$ $(M+H)^+$ 282.149886 found 282.14933; HPLC (S,S-WHELK, 1.0% isopropanol in hexane, 1.0 mL/min, 1 mg/mL, 50 min, UV 254 nm) retention times of 28.7 min (major) and 40.3 min (minor), 89% ee.

General procedure for Rh_2(*R*-BTPCP)$_4$-catalyzed cyclopropanation/Cope rearrangement

To a 25 mL flame-dried round-bottom flask, kept under a dry atmosphere of argon, was added diene (2.0 mmol, 5.0 equiv), dry and degassed dichloromethane (1.0 mL) and Rh_2(*R*-BTPCP)$_4$ (7.0 mg, 0.01 equiv). The given diazo compound **(**0.4 mmol, 1.0 equiv), dissolved in dry and degassed dichloromethane (2.0 mL), was then added to the former solution drop-wise over 1.0 hour at -40 ^oC. The mixture was allowed to stir to room temperature overnight, and was then concentrated *in vacuo*. The crude residue was analyzed by ^1H NMR and purified by flash column chromatography (hexanes/ethyl acetate) to afford the desired products.

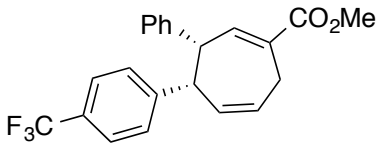


(3*R*,4*S*)-methyl 3,4-diphenylcyclohepta-1,5-dienecarboxylate (**3.98**)

This compound was prepared by the general procedure for Rh_2(*R*-BTPCP)$_4$-catalyzed cyclopropanation/Cope rearrangement. Derived from (*E*)-methyl 2-diazo-4-phenylbut-3-enoate (**3.1**) (0.4 mmol, 80.8 mg, 1.0 equiv) and (*E*)-buta-1,3-dien-1-ylbenzene (**3.95**) (2.0 mmol, 260 mg, 5.0 equiv). The crude residue was analyzed by ^1H NMR and purified by flash column chromatography (hexanes/ethyl acetate = 50/1) to afford the product

(**3.98**) as a colorless oil (68.3 mg, 56%). The NMR spectrum is consistent with previously reported data.[15]

^{1}H NMR (400 MHz, $CDCl_3$): δ 7.23-7.12 (m, 7H), 6.90-6.88 (m, 2H), 6.82-6.80 (m, 2H), 6.01-5.95 (m, 1H), 5.78 (ddd, *J* = 11.4, 5.6, 2.7 Hz, 1H), 4.42 (s, 1H), 3.89 (s, 1H), 3.78 (s, 3H), 3.55-3.39 (m, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 167.7, 144.5, 140.5, 139.8, 133.1, 132.3, 129.8, 129.1, 127.8, 127.5, 126.7, 126.6, 126.3, 52.0, 50.1, 49.6, 25.7; HPLC: (S,S-Whelk, 1.5% isopropanol in hexane, 0.7 mL/min, 1 mg/mL, 30 min, UV 254 nm) retention times of 14.1 min (minor) and 15.8 min (major), 87% ee.



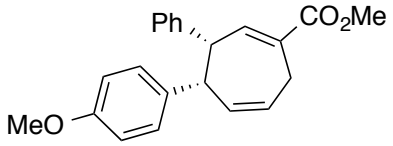
(3*R*,4*S*)-methyl 3-phenyl-4-(4-(trifluoromethyl)phenyl)cyclohepta-1,5-dienecarboxylate (**3.99**)

This compound was prepared by the general procedure for Rh_2(*R*-BTPCP)$_4$-catalyzed cyclopropanation/Cope rearrangement. Derived from (*E*)-methyl 2-diazo-4-phenylbut-3-enoate (**3.1**) (0.4 mmol, 80.8 mg, 1.0 equiv) and (*E*)-1-(buta-1,3-dien-1-yl)-4-(trifluoromethyl)benzene (**3.96**) (2.0 mmol, 396 mg, 5.0 equiv). The crude residue was analyzed by ^{1}H NMR and purified by flash column chromatography (hexanes/ethysl acetate = 50/1) to afford the product **3.99** as a colorless oil (105.2 mg, 71%).

$[\alpha]^{20}_{D:}$ -60.7° (*c* = 3.57, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.40 (d, *J* = 8.2 Hz, 2H), 7.26-7.19 (m, 3H), 7.08 (dd, *J* = 6.7, 2.7 Hz, 1H), 6.89-6.86 (m, 4H), 6.03-5.97 (m, 1H),

[15] Davies, H. M. L.; Stafford, D. G.; Doan, B. D. Houser, J. H. *J. Am. Chem. Soc.* **1998**, *120*, 3326.

5.72 (ddd, J = 11.4, 5.6, 2.9, 1H), 4.44 (s, 1H), 3.91-3.89 (m, 1H), 3.77 (s, 3H), 3.56-3.49 (m, 1H), 3.44-3.37 (m, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 167.5, 143.9, 143.6, 140.0, 132.7, 132.0, 130.1, 129.4, 129.1, 128.9, 128.8, 128.6, 128.5, 128.0, 126.9, 125.6, 124.4, 124.3, 122.9, 52.0, 50.0, 49.2, 25.7; IR (film): 3026, 2952, 1712, 1325; HRMS (APCI) calcd for $C_{22}H_{21}F_3O_2$ $(M+H)^+$ 373.14153 found 373.14045; HPLC: (OJH, 1.0% isopropanol in hexane, 1.0 mL/min, 1 mg/mL, 30 min, UV 254 nm) retention times of 6.2 min (minor) and 7.7 min (major), 91% ee.



(3*R*,4*S*)-methyl 4-(4-methoxyphenyl)-3-phenylcyclohepta-1,5-dienecarboxylate (**3.100**)

This compound was prepared by the general procedure for Rh_2(*R*-BTPCP)$_4$-catalyzed cyclopropanation/Cope rearrangement. Derived from (*E*)-methyl 2-diazo-4-phenylbut-3-enoate (**3.1**) (0.4 mmol, 80.8 mg, 1.0 equiv) and (*E*)-1-(buta-1,3-dien-1-yl)-4-methoxybenzene (**3.97**) (2.0 mmol, 320 mg, 5.0 equiv). The crude residue was analyzed by ^{1}H NMR and purified by flash column chromatography (hexanes/ethyl acetate = 50/1) to afford the product (**3.100**) as a colorless oil (79.6 mg, 60%).

$[\alpha]^{20}_{D:}$ -2.1^o (*c* = 3.01, MeOH); ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.27-7.21 (m, 3H), 7.11 (dd, J = 6.7, 2.7 Hz, 1H), 6.90 (dd, J = 6.6, 2.9 Hz, 1H), 6.71 (s, 4H), 5.95-5.94 (m, 1H), 5.74 (ddd, J = 11.4, 5.6, 2.7 Hz, 1H), 4.39 (s. 1H), 3.79 (s. 3H), 3.77 (s, 3H), 3.52-3.46 (m, 1H), 3.42-3.37 (m, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 167.7, 158.4, 144.7, 140.8, 133.4, 132.4, 131.8, 130.8, 129.0, 127.8, 126.7, 125.9, 112.9, 55.1, 52.0, 49.7, 49.4, 25.7; IR (film): 3010, 2950, 2359, 1708, 1509; HRMS (APCI) calcd for $C_{22}H_{24}O_3$ $(M+H)^+$

335.16471 found 335.16378; HPLC: (S,S-Whelk, 1.5% isopropanol in hexane, 0.7 mL/min, 1 mg/mL, 30 min, UV 254 nm) retention times of 23.9 min (minor) and 26.0 min (major), 89% ee.

General procedure for Rh_2(*R*-BTPCP)$_4$-catalyzed C–H functionalization

To a 25 mL flame-dried round-bottom flask, kept under a dry atmosphere of argon, was added cyclohexa-1,4-diene or methyl-1,2-dihydronaphthalene (2.0 mmol, 5.0 equiv), dry and degassed dichloromethane (1.0 mL) and Rh_2(*R*-BTPCP)$_4$ (7.0 mg, 0.01 equiv). The given diazo compound **(**0.4 mmol, 1.0 equiv), dissolved in dry and degassed dichloromethane (2.0 mL), was then added to the former solution drop-wise over 1 hour at ambient temperature. The mixture was allowed to stir for overnight, and was then concentrated *in vacuo*. The crude residue was analyzed by ^{1}H NMR and purified by flash column chromatography (hexanes/ethyl acetate) to give the desired products

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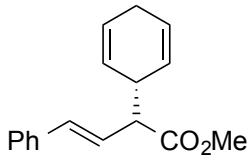
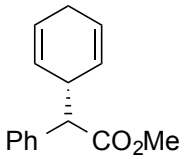


(*S*,*E*)-methyl 2-(cyclohexa-2,5-dien-1-yl)-4-phenylbut-3-enoate (**3.102**)

This compound was prepared by the general procedure for Rh_2(*R*-BTPCP)$_4$-catalyzed C–H functionalization. Derived from (*E*)-methyl 2-diazo-4-phenylbut-3-enoate (**3.1**) (0.4 mmol, 80.8 mg, 1.0 equiv) and cyclohexa-1,4-diene (**3.101**) (2.0 mmol, 160 mg, 5.0 equiv). The crude residue was analyzed by ^{1}H NMR and purified by flash column chromatography (hexanes/ethyl acetate = 50/1) to afford the product (**3.102**) as a

colorless oil (11.2 mg, 11%). The NMR spectral data is consistent with previously reported data.[6]

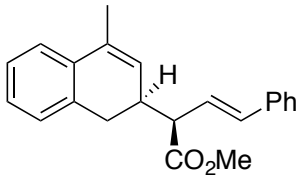
^{1}H NMR (400 MHz, $CDCl_3$): δ 7.37-7.19 (m, 5H), 6.44 (d, *J* = 15.4 Hz, 1H), 6.21 (dd, *J* = 16.0, 9.4 Hz, 1H), 5.82-5.78 (m, 2H), 5.72-5.68 (m, 1H), 5.59-5.55 (m, 1H), 3.70 (s, 3H), 3.29-3.26 (m, 1H), 3.13 (dd, *J* = 9.4, 7.4 Hz, 1H), 2.63-2.59 (m, 2H); HPLC: (OJH, 0.5% isopropanol in hexane, 0.5 mL/min, 1 mg/mL, 30 min, UV 254 nm) retention times of 20.7 min (minor) and 29.6 min (major), 8% ee.



(*R*)-methyl 2-(cyclohexa-2,5-dien-1-yl)-2-phenylacetate (**3.105**)

This compound was prepared by the general procedure for Rh_2(*R*-BTPCP)$_4$-catalyzed C–H functionalization. Derived from methyl 2-diazo-2-phenylacetate (**3.5**) (0.4 mmol, 70.4 mg, 1.0 equiv) and cyclohexa-1,4-diene (**3.101**) (2.0 mmol, 160 mg, 5.0 equiv). The crude residue was analyzed by ^{1}H NMR and purified by flash column chromatography (hexanes/ethyl acetate = 50/1) to afford the product (**3.105**) as a colorless oil (51 mg, 56%). The NMR spectrum is consistent with previously reported data.[6]

^{1}H NMR (400 MHz, $CDCl_3$): δ 7.32-7.24 (m, 5H), 5.81-5.77 (m, 1H), 5.71-5.65 (m, 2H), 5.26-5.22 (m, 1H), 3.66 (s. 1H), 3.47-3.45 (m, 1H), 3.41-3.39 (m, 1H), 2.61-2.58 (m, 2H); HPLC: (OJH, 0.5% isopropanol in hexane, 0.5 mL/min, 1 mg/mL, 30 min, UV 254 nm) retention times of 13.5 min (minor) and 15.5 min (major), 26% ee.



(*R*,*E*)-methyl 2-((*S*)-4-methyl-1,2-dihydronaphthalen-2-yl)-4-phenylbut-3-enoate (**3.107**)

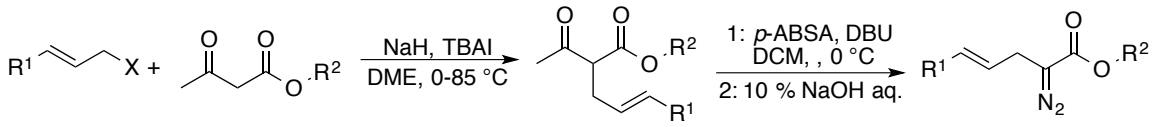
This compound was prepared by the general procedure for Rh_2(*R*-BTPCP)$_4$-catalyzed C–H functionalization. Derived from (*E*)-methyl 2-diazo-4-phenylbut-3-enoate (**3.1**) (0.4 mmol, 80.8 mg, 1.0 equiv) and methyl-1,2-dihydronaphthalene (**3.106**) (2 mmol, 5.0 equiv). The crude residue was analyzed by ^{1}H NMR and purified by flash column chromatography (hexanes/ethyl acetate = 50/1) to afford the product (**3.107**) as a colorless oil (117 mg, 92%). The NMR spectrum is consistent with previously reported data.[16]

^{1}H NMR (400 MHz, $CDCl_3$): δ 7.36-7.07 (m, 9H), 6.42 (d, *J* = 15.9 Hz, 1H), 6.14 (dd, *J* = 15.9, 9.8 Hz, 1H), 5.73 (d, *J* = 3.1 Hz, 1H), 3.70 (s, 3H), 3.11 (t, *J* = 9.5 Hz, 1H), 2.89-2.83 (m, 2H), 2.74-2.70 (m, 1H), 2.07 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 173.9, 136.9, 135,5, 134.6, 133.9, 128.8, 128.0, 127.9, 127.4, 126.8, 126.6, 126.5, 126.3, 123.3, 53.4, 52.1, 36.3, 31.9, 19.6; HPLC: (OD, 2.0% isopropanol in hexane, 0.8 mL/min, 1 mg/mL, 30 min, UV 254 nm) retention times of 8.9 min (minor) and 10.5 min (major), 98% ee.

Experimental Data for Chapter IV:

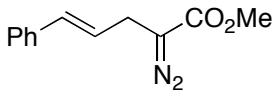
General procedure for the synthesis of α-allyldiazoacetates

[16] Davies, H. M. L.; Jin, Q. *J. Am. Chem. Soc.* **2004**, *126*, 10862.



Under an argon atmosphere, a solution of acetoacetate (1.5 equiv) in anhydrous 1,2-dimethoxyethane was added drop-wise to a stirred suspension of NaH (dry powder, 95%, 1.5 equiv) in anhydrous 1,2-dimethoxyethane at 0 °C in 1.0 hour. Then, *n*-Bu_4NI (0.1 equiv) was added in one portion, followed by slow addition of allyl halide derivative (1.0 equiv) in anhydrous 1,2-dimethoxyethane at 0 °C in 1 hour. Then, the resulting mixture was heated at 85 °C overnight. The mixture was cooled to 0 °C, diluted with 1 N HCl, and extracted with diethyl ether. The combined organic extracts were washed by brine, dried over anhydrous $MgSO_4$ and concentrated *in vacuo*. After flash chromatographic purification, the resulting α-allyl-β-ketoester was used directly without full characterization in the next step.

To a stirred solution of α-allyl-β-ketoester (1.0 equiv) and *p*-acetamidobenzenesulfonyl azide (*p*-ABSA) (2.0 equiv) in dichloromethane, DBU (4.0 equiv) was added dropwise at 0 °C. The reaction mixture was then stirring for another 2-3 h. Then, 10% NaOH aqueous was added at 0 °C. The resulting mixture was warmed to room temperature. The crude α-allyldiazoester was extracted with dichloromethane, washed by brine, dried over anhydrous $MgSO_4$, concentrated *in vacuo*, and chromatographed to afford the corresponding α-allyldiazoacetates.



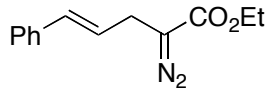
(*E*)-methyl 2-diazo-5-phenylpent-4-enoate (**4.5**)

Prepared according to the general procedure for the synthesis of α-allyldiazoacetates using cinnamyl chloride (23.0 g, 151 mmol, 1.0 equiv) dissolved in anhydrous 1,2-dimethoxyethane (50 mL), methyl acetoacetate (26.2 g, 226 mmol, 1.5 equiv) dissolved in anhydrous 1,2-dimethoxyethane (50 mL), sodium hydride (dry powder, 95%, 5.5 g, 226 mmol, 1.5 equiv) dissolved in anhydrous 1,2-dimethoxyethane (50 mL) and *n*-Bu_4NI (5.6 g, 15.1 mmol, 0.1 equiv). After removal of all volatile compounds, the resulting α-allyl-β-ketoester derivative was obtained after flash chromatographic purification and used without full characterization in the next step.

The resulting α-allyl-β-ketoester derivative (2.32 g, ca. 10 mmol) was dissolved in dichloromethane (60 mL) and *p*-acetamidobenzenesulfonyl azide (*p*-ABSA) (4.8 g, 20 mmol) was added at 0 °C under argon atmosphere. DBU (6.0 ml, 40 mmol) was added drop-wise at 0 °C in 1.0 hour. The reaction mixture was then stirred for another 3 h. Then, 10% NaOH (20 mL) was added at 0 °C. The resulting mixture was warmed to room temperature. The crude α-allyldiazoester was extracted with dichloromethane (3 x 20 mL), washed by brine (3 x 10 mL), dried over anhydrous $MgSO_4$. Flash chromatographic purification (hexanes/ethyl acetate = 100/1) afforded the product (**4.5**) (1.46 g, 67%, two steps) as a yellow oil. The NMR spectrum is consistent with previously reported data.[17]

^{1}H NMR (400 MHz, $CDCl_3$): δ 7.36−7.29 (m, 4H), 7.24-7.21 (m, 1H), 6.81-6.79 (m, 2H), 6.49 (d, J = 16.0 Hz, 1H), 6.19 (dt, J = 6.8, 16.0 Hz, 1H), 3.76 (s, 3H), 3.20 (d, J = 6.8 Hz, 1H).

[17] Taber, D. F.; Herr, R. J.; Pack, S. K.; Geremia, J. M. *J. Org. Chem.* **1996**, *61*, 2908.



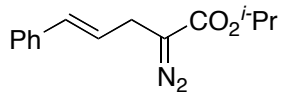
(*E*)-ethyl 2-diazo-5-phenylpent-4-enoate (**4.16a**)

Prepared according to the general procedure for the synthesis of α-allyldiazoacetates using cinnamyl bromide (3.92 g, 20 mmol, 1.0 equiv) dissolved in anhydrous 1,2-dimethoxyethane (20 mL), ethyl acetoacetate (3.90 g, 30 mmol, 1.5 equiv) dissolved in anhydrous 1,2-dimethoxyethane (20 mL), sodium hydride (dry powder, 95%, 758 mg, 30 mmol, 1.5 equiv) dissolved in anhydrous 1,2-dimethoxyethane (20 mL) and *n*-Bu_4NI (738 mg, 2.0 mmol, 0.1 equiv). After flash chromatographic purification, the resulting α-allyl-β-ketoester derivative was obtained and used without full characterization.

The resulting α-allyl-β-ketoester derivative (1.23 g, ca. 5 mmol, 1.0 equiv) was dissolved in dichloromethane (40 mL), *p*-acetamidobenzenesulfonyl azide (*p*-ABSA) (2.4 g, 10 mmol, 2.0 equiv) was added at 0 °C under argon atmosphere. DBU (3.0 ml, 20 mmol, 4.0 equiv) was added drop-wise at 0 °C in 1 hour. The reaction mixture was then stirred for another 2.0 h. Then, 10% NaOH (15 mL) was added at 0 °C. The resulting mixture was warmed to room temperature. The crude α-allyldiazoester was extracted with dichloromethane (3 x 20 mL), washed by brine (3 x 10 mL), dried over anhydrous $MgSO_4$. Flash chromatographic purification (hexanes/ethyl acetate = 50/1) afforded the product (**4.16a**) (665.9 mg, 58%, two steps) as a yellow oil.

^{1}H NMR (400 MHz, $CDCl_3$): δ 7.35-7.22 (m, 5H), 6.48 (d, *J* = 16.0 Hz, 1H), 6.19 (dt, *J* = 6.4, 16.0 Hz, 1H), 4.23 (q, *J* = 7.6 Hz, 2H), 3.20 (d, *J* = 7.2 Hz, 2H), 1.27 (t, *J* = 7.6 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 136.5, 132.5, 128.4, 127.4, 126.1, 123.9, 60.7, 26.6,

14.4; IR (neat): 2982, 2080, 1686, 1370, 1108; HRMS (APCI) calcd for $C_{13}H1_5O_2N_2$ $(M+H)^+$ 231.11280 found 231.11253.

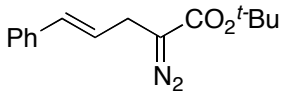


(*E*)-isopropyl 2-diazo-5-phenylpent-4-enoate (**4.16b**)

Prepared according to the general procedure for the synthesis of α-allyldiazoacetates using cinnamyl bromide (3.92 g, 20 mmol, 1.0 equiv) dissolved in anhydrous 1,2-dimethoxyethane (20 mL), isopropyl acetoacetate (4.32 g, 30 mmol, 1.5 equiv) dissolved in anhydrous 1,2-dimethoxyethane (20 mL), sodium hydride (dry powder, 95%, 758 mg, 30 mmol, 1.5 equiv) dissolved in anhydrous 1,2-dimethoxyethane (15 mL) and *n*-Bu_4NI (738 mg, 2.0 mmol, 0.1 equiv). After general work up, the resulting α-allyl-β-ketoester derivative was obtained and used without full characterization.

The resulting α-allyl-β-ketoester derivative (1.3 g, ca. 5.0 mmol, 1.0 equiv) was dissolved in dichloromethane (30 mL) and *p*-acetamidobenzenesulfonyl azide (*p*-ABSA) (2.4 g, 10 mmol, 2.0 equiv) was added at 0 °C under argon atmosphere. DBU (3.0 mL, 20 mmol, 4.0 equiv) was added drop-wise at 0 °C in 1 hour. The reaction mixture was then stirred for another 2 h. Then, 10% NaOH (15 mL) was added at 0 °C. The resulting mixture was warmed to room temperature. The crude α-allyldiazoester was extracted with dichloromethane (3 x 20 mL), washed by brine (3 x 10 mL), dried over anhydrous $MgSO_4$. Flash chromatographic purification (hexanes/ethyl acetate = 50/1) afforded the product (**4.16b**) (507.9 mg, 42%, two steps) as a yellow oil.

^{1}H NMR (400 MHz, $CDCl_3$): δ 7.38-7.22 (m, 5H), 6.50 (d, *J* = 15.6 Hz, 1H), 6.20 (dt, *J* = 6.9, 15.6 Hz, 1H), 5.15-5.09 (m, 1H), 3.20 (d, *J* = 6.9 Hz, 2H), 1.27 (d, *J* = 6.3 Hz, 6H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 136.4, 132.4, 128.3, 127.3, 126.0, 123.9, 68.1, 26.5, 21.8; IR (neat): 2980, 2078, 1684, 1364, 1102; HRMS (ESI) calcd for $C_{14}H_{17}O_2N_2$ $(M+H)^+$ 245.12845 found 245.12819.



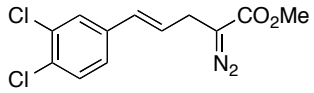
(*E*)-*tert*-butyl 2-diazo-5-phenylpent-4-enoate (**4.16c**)

Prepared according to the general procedure for the synthesis of α-allyldiazoacetates using cinnamyl bromide (3.92 g, 20 mmol, 1.0 equiv) dissolved in anhydrous 1,2-dimethoxyethane (20 mL), isopropyl acetoacetate (4.74 g, 30 mmol, 1.5 equiv) dissolved in anhydrous 1,2-dimethoxyethane (20 mL), sodium hydride (dry powder, 95%, 758 mg, 30 mmol, 1.5 equiv) dissolved in anhydrous 1,2-dimethoxyethane (15 mL) and *n*-Bu_4NI (738 mg, 2.0 mmol, 0.1 equiv). After general work up, the crude ester was obtained and used without full characterization.

The resulting α-allyl-β-ketoester derivative (1.37 g, ca. 5.0 mmol, 1.0 equiv) was dissolved in dichloromethane (30 mL) and *p*-acetamidobenzenesulfonyl azide (*p*-ABSA) (2.4 g, 10 mmol, 2.0 equiv) was added at 0 °C under argon atmosphere. DBU (3.0 mL, 20 mmol, 4.0 equiv) was added drop-wise at 0 °C in 1.0 hour. The reaction mixture was then stirred for another 2.0 h. Then, 10% NaOH (15 mL) was added at 0 °C. The resulting mixture was warmed to room temperature. The crude α-allyldiazoester was extracted with dichloromethane (3 x 20 mL), washed by brine (3 x 10 mL), dried over anhydrous

$MgSO_4$. Flash chromatographic purification (hexanes/ethyl acetate = 50/1) afforded the product (**4.16c**) (669.9 mg, 52%, two steps) as a yellow oil.

^{1}H NMR (400 MHz, $CDCl_3$): δ 7.35-7.21 (m, 5H), 6.47 (d, J = 16.0 Hz, 1H), 6.17 (dt, J = 7.2, 16.0 Hz, 1H), 3.14 (d, J = 7.2 Hz, 2H), 1.48 (s, 9H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 136.7, 132.5, 128.5, 127.5, 126.2, 124.2, 81.2, 28.3, 26.7; IR (neat): 2977, 2076, 1682, 1392, 1108; HRMS (APCI) calcd for $C_{15}H_{19}O_2$ $(M\text{-}N_2+H)^+$ 231.13796 found 231.13762.



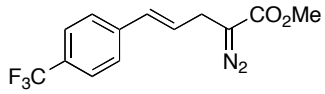
(*E*)-methyl 2-diazo-5-(3,4-dichlorophenyl)pent-4-enoate (**4.16d**)

Prepared according to the general procedure for the synthesis of α-allyldiazoacetates using (*E*)-4-(3-bromoprop-1-en-1-yl)-1,2-dichlorobenzene (12.0 g, 45.5 mmol, 1.0 equiv) dissolved in anhydrous 1,2-dimethoxyethane (50 mL), methyl acetoacetate (7.92 g, 68.3 mmol, 1.5 equiv) dissolved in anhydrous 1,2-dimethoxyethane (50 mL), sodium hydride (dry powder, 95%, 1.73 g, 68.3 mmol, 1.5 equiv) dissolved in anhydrous 1,2-dimethoxyethane (25 mL) and *n*-Bu_4NI (1.68 g, 4.55 mmol, 0.1 equiv). After flash chromatographic purification, the resulting α-allyl-β-ketoester was obtained and used directly without full characterization in the next step.

The obtained ester derivative (1.50 g, ca. 5.0 mmol, 1.0 equiv) was dissolved in dichloromethane (40 mL) and *p*-acetamidobenzenesulfonyl azide (*p*-ABSA) (2.4 g, 10 mmol, 2.0 equiv) was added at 0 °C under argon atmophere. DBU (3.0 mL, 20 mmol, 4.0 equiv) was added drop-wise at 0 °C in 1.0 hour. The reaction mixture was then stirred for another 2.0 h. Then, 10% NaOH (15 mL) was added at 0 °C. The resulting mixture was warmed to room temperature. The crude α-allyldiazoester was extracted with

dichloromethane (3 x 20 mL), washed by brine (3 x 10 mL), dried over anhydrous $MgSO_4$. Flash chromatographic purification (hexanes/ethyl acetate = 50/1) afforded the product (**4.16d**) (901.1 mg, 63%, two steps) as a yellow oil.

^{1}H NMR (600 MHz, $CDCl_3$): δ 7.43 (d, J = 2.0 Hz, 1H), 7.36 (d, J = 8.3 Hz, 1H), 7.17 (dd, J = 2.0, 8.3 Hz, 1H), 3.79 (s, 3H), 3.20 (d, J = 6.7 Hz, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 166.8, 136.5, 132.2, 130.8, 130.0, 129.8, 127.6, 126.0, 125.2, 51.7, 26.5; IR (neat): 2977, 2076, 1682, 1392, 1108; HRMS (APCI) calcd for $C_{12}H_{11}O_2N_2Cl_2$ $(M+H)^+$ 285.01921 found 285.01965.



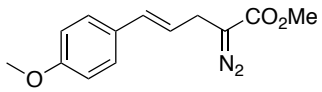
(*E*)-methyl 2-diazo-5-(4-(trifluoromethyl)phenyl)pent-4-enoate (**4.16e**)

Prepared according to the general procedure for the synthesis of α-allyldiazoacetates using (*E*)-1-(3-bromoprop-1-en-1-yl)-4-(trifluoromethyl)benzene (6.0 g, 23.0 mmol, 1.0 equiv) dissolved in anhydrous 1,2-dimethoxyethane (20 mL), methyl acetoacetate (4.0 g, 34.5 mmol, 1.5 equiv) dissolved in anhydrous 1,2-dimethoxyethane (25 mL), sodium hydride (dry powder, 95%, 872 mg, 34.5 mmol, 1.5 equiv) dissolved in anhydrous 1,2-dimethoxyethane (25 mL) and *n*-Bu_4NI (849 mg, 2.3 mmol, 0.1 equiv). After general work up, the resulting α-allyl-β-ketoester was obtained and used directly without full characterization.

The resulting α-allyl-β-ketoester derivative (1.5 g, ca. 5.0 mmol, 1.0 equiv) was dissolved in dichloromethane (30 mL) and *p*-acetamidobenzenesulfonyl azide (*p*-ABSA) (2.4 g, 10 mmol, 2.0 equiv) was added at 0 °C under argon atmophere. DBU (3.0 ml, 20 mmol, 4.0 equiv) was added drop-wise at 0 °C in 1 hour. The reaction mixture was then stirred for

another 2 h. Then, 10% NaOH (20 mL) was added at 0 °C. The resulting mixture was warmed to room temperature. The crude α-allyldiazoester was extracted with dichloromethane (3 x 20 mL), washed by brine (3 x 10 mL), dried over anhydrous $MgSO_4$. Flash chromatographic purification (hexanes/ethyl acetate = 100/1) afforded the product (**4.16e**) (440.2 mg, 29%, two steps) as a yellow oil.

^{1}H NMR (400 MHz, $CDCl_3$): δ 7.54 (d, *J* = 8.2 Hz, 2H), 7.43 (d, *J* = 8.2 Hz, 2H), 6.52 (d, *J* = 16.0 Hz, 1H), 6.29 (dt, *J* = 6.8, 16.0 Hz, 1H), 3.78 (s, 3H), 3.22 (d, *J* = 6.8 Hz, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 167.1, 140.0, 131.1, 129.4, 129.1, 128.7, 128.1, 126.9, 126.3, 126.1, 125.42, 125.38, 125.34, 125.30, 122.7, 120.0, 51.9, 26.7; IR (neat): 2955, 1716, 1620, 1326, 1121, 1068; HRMS (APCI) calcd for $C_{13}H_{12}O_2F_3N_2$ $(M+H)^+$ 285.08454 found 285.08401.

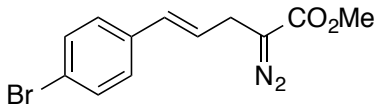


(*E*)-methyl 2-diazo-5-(4-methoxyphenyl)pent-4-enoate (**4.16f**)

Prepared according to the general procedure for the synthesis of α-allyldiazoacetates using (*E*)-1-(3-bromoprop-1-en-1-yl)-4-methoxybenzene (2.2 g, 9.7 mmol, 1.0 equiv) dissolved in anhydrous 1,2-dimethoxyethane (20 mL), methyl acetoacetate (1.7 g, 14.6 mmol, 1.5 equiv) dissolved in anhydrous 1,2-dimethoxyethane (16 mL), sodium hydride (dry powder, 95%, 369 mg, 14.6 mmol, 1.5 equiv) dissolved in anhydrous 1,2-dimethoxyethane (20 mL) and *n*-Bu_4NI (358 mg, 0.97 mmol, 0.1 equiv). After general work up, the resulting α-allyl-β-ketoester was obtained and used directly without full full characterization.

The resulting α-allyl-β-ketoester derivative (2.6 g, ca. 10.0 mmol, 1.0 equiv) was dissolved in dichloromethane (50 mL) and *p*-acetamidobenzenesulfonyl azide (*p*-ABSA) (4.8 g, 20 mmol, 2.0 equiv) was added at 0 °C under argon atmophere. DBU (6.0 ml, 40 mmol, 4.0 equiv) was added drop-wise at 0 °C in 1 hour. The reaction mixture was then stirred for another 2.0 h. Then, 10% NaOH (20 mL) was added at 0 °C. The resulting mixture was warmed to room temperature. The crude α-allyldiazoester was extracted with dichloromethane (3 x 20 mL), washed by brine (3 x 10 mL), dried over anhydrous $MgSO_4$. Flash chromatographic purification (hexanes/ethyl acetate = 100/1) afforded the product (**4.16f**) (1.29 mg, 54%, two steps) as a sticky yellow oil.

^{1}H NMR (400 MHz, $CDCl_3$): δ 7.29 (d, *J* = 8.8 Hz, 2H), 6.84 (d, *J* = 8.8 Hz, 2H), 6.44 (d, *J* = 15.6 Hz, 1H), 6.04 (dt, *J* = 6.8, 15.6 Hz, 1H), 3.79 (s, 3H), 3.78 (s, 3H), 3.18 (d, *J* = 6.8 Hz, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 159.2, 132.1, 129.4, 127.4, 121.6, 113.9, 55.2, 51.9, 26.8; IR (neat): 2953, 2837, 2080, 1689, 1511, 1247; HRMS (APCI) calcd for $C_{13}H_{15}O_3N_2$ $(M+H)^+$ 247.10772 found 247.10796.



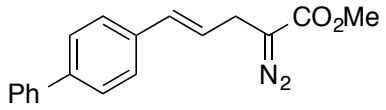
(*E*)-methyl 5-(4-bromophenyl)-2-diazopent-4-enoate (**4.16g**)

Prepared according to the general procedure for the synthesis of α-allyldiazoacetates using (*E*)-1-bromo-4-(3-bromoprop-1-en-1-yl)benzene (5.1 g, 18.6 mmol, 1.0 equiv) dissolved in anhydrous 1,2-dimethoxyethane (20 mL), methyl acetoacetate (3.2 g, 27.9 mmol, 1.5 equiv) dissolved in anhydrous 1,2-dimethoxyethane (20 mL), sodium hydride (dry powder, 95%, 705 mg, 27.9 mmol, 1.5 equiv) dissolved in anhydrous 1,2-

dimethoxyethane (20 mL) and *n*-Bu_4NI (686 mg, 1.86 mmol, 0.1 equiv). After general work up, the resulting α-allyl-β-ketoester was obtained and used without full characterization.

The resulting α-allyl-β-ketoester derivative (1.55 g, ca. 5.0 mmol, 1.0 equiv) was dissolved in dichloromethane (50 mL) and *p*-acetamidobenzenesulfonyl azide (*p*-ABSA) (2.4 g, 10.0 mmol, 2.0 equiv) was added at 0 °C under argon atmophere. DBU (3.0 ml, 20 mmol, 4.0 equiv) was added drop-wise at 0 °C in 1 hour. The reaction mixture was then stirred for another 2.0 h. Then, 10% NaOH (20 mL) was added at 0 °C. The resulting mixture was warmed to room temperature. The crude α-allyldiazoester was extracted with dichloromethane (3 x 20 mL), washed by brine (3 x 10 mL), dried over anhydrous $MgSO_4$. Flash chromatographic purification (hexanes/ethyl acetate = 50/1) afforded the product (**4.16g**) (977.8 mg, 66%, two steps) as a yellow oil.

^{1}H NMR (400 MHz, $CDCl_3$): δ 7.43 (d, *J* = 8.8 Hz, 2H), 7.23 (d, *J* = 8.8 Hz, 2H), 6.44 (d, *J* = 16.0 Hz, 1H), 6.20 (dt, *J* = 7.2, 16.0 Hz, 1H), 3.79 (s, 3H), 3.20 (d, *J* = 7.2 Hz, 2H), 3.01 (d, *J* = 7.6 Hz, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 135.5, 131.6, 131.5, 127.8, 124.9, 121.4, 52.0, 26.8; IR (neat): 2950, 2078, 1686, 1339; HRMS (APCI) calcd for $C_{12}H_{12}O_2N_2Br$ $(M+H)^+$ 295.00767found 295.00801.



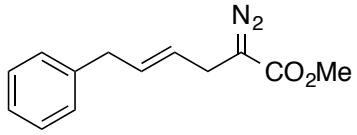
(*E*)-methyl 5-([1,1'-biphenyl]-4-yl)-2-diazopent-4-enoate (**4.16h**)

Prepared according to the general procedure for the synthesis of α-allyldiazoacetates using (*E*)-4-(3-bromoprop-1-en-1-yl)-1,1'-biphenyl (5.16 g, 19.0 mmol, 1.0 equiv)

dissolved in anhydrous 1,2-dimethoxyethane (60 mL, note: 15 mL dichloromethane was also added to increase the solubility), and the resulting solution in pressure constant funnel under argon was dropped over 1.0 hour, methyl acetoacetate (3.48 g, 30 mmol, 1.58 equiv) dissolved in anhydrous 1,2-dimethoxyethane (20 mL), sodium hydride (dry powder, 95%, 758 mg, 30 mmol, 1.5 equiv) dissolved in anhydrous 1,2-dimethoxyethane (20 mL) and *n*-Bu_4NI (738 mg, 1.9 mmol, 0.1 equiv). After general work up, the resulting α-allyl-β-ketoester was obtained and used without full characterization.

The resulting α-allyl-β-ketoester derivative (0.8 g, ca. 2.6 mmol, 1.0 equiv) was dissolved in dichloromethane (50 mL) and *p*-acetamidobenzenesulfonyl azide (*p*-ABSA) (1.25 g, 5.2 mmol, 2.0 equiv) was added at 0 °C under argon atmosphere. DBU (1.54 ml, 10.4 mmol, 4.0 equiv) was added drop-wise at 0 °C in 1.0 hour. The reaction mixture was then stirred for another 2.0 h. Then, 10% NaOH (20 mL) was added at 0 °C. The resulting mixture was warmed to room temperature. The crude α-allyldiazoester was extracted with dichloromethane (3 x 30 mL), washed by brine (3 x 10 mL), dried over anhydrous $MgSO_4$. Flash chromatographic purification (hexanes/ethyl acetate = 50/1) afforded (**4.16h**) (467.3 mg, 62%, two steps) as a yellow solid.

Mp: 71-72 °C; ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.66-7.59 (m, 4H), 7.51-7.47 (m, 4H), 7.42-7.38 (m, 1H), 6.59 (d, J = 15.6 Hz, 1H), 6.29 (dt, J = 6.8, 15.6 Hz, 1H), 3.85 (s, 3H), 3.27 (d, J = 7.2 Hz, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 140.4, 140.2, 135.5, 132.1, 128.6, 127.2, 127.1, 126.7, 126.6, 123.9, 51.9, 26.7; IR (neat): 3031, 2080, 1692, 1437, 1341; HRMS (APCI) calcd for $C_{18}H_{17}O_2$ $(M\text{-}N_2+H)^+$ 265.12231 found 265.12283.



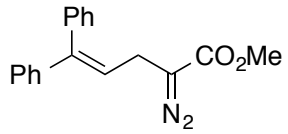
(*E*)-methyl 2-diazo-6-phenylhex-4-enoate (**4.16i**)

Prepared according to the general procedure for the synthesis of α-allyldiazoacetates using (*E*)-(4-bromobut-2-en-1-yl)benzene (3.78 g, 18.0 mmol, 1.0 equiv) dissolved in anhydrous 1,2-dimethoxyethane (50 mL), methyl acetoacetate (3.13 g, 27 mmol, 1.5 equiv) dissolved in anhydrous 1,2-dimethoxyethane (20 mL), sodium hydride (dry powder, 95%, 682 mg, 27 mmol, 1.5 equiv) dissolved in anhydrous 1,2-dimethoxyethane (20 mL) and *n*-Bu_4NI (664 mg, 1.8 mmol, 0.1 equiv). After general work up, the resulting α-allyl-β-ketoester was obtained and used without full characterization.

The resulting α-allyl-β-ketoester derivative (1.1 g, ca. 4.5 mmol, 1.0 equiv) was dissolved in dichloromethane (20 mL) and *p*-acetamidobenzenesulfonyl azide (*p*-ABSA) (3.24 g, 13.5 mmol, 3.0 equiv) was added at 0 °C under argon atmosphere. DBU (4.0 ml, 27 mmol, 6.0 equiv) was added drop-wise at 0 °C in 1.0 hour. The reaction mixture was then stirred for another 2.0 h. Then, 10% NaOH (20 mL) was added at 0 °C. The resulting mixture was warmed to room temperature. The crude α-allyldiazoester was extracted with dichloromethane (3 x 20 mL), washed by brine (3 x 10 mL), dried over anhydrous $MgSO_4$. Flash chromatographic purification (hexanes/ethyl acetate = 50/1) afforded the product (**4.16i**) (462.2 mg, 45%, two steps) as a yellow sticky oil.

^{1}H NMR (400 MHz, $CDCl_3$): δ 7.29-7.13 (m, 5H), 5.76-5.68 (m, 1H), 5.68-5.45 (m, 1H), 3.74 (s, 3H), 3.34 (d, J = 7.0 Hz, 2H), 3.01 (d, J = 7.0 Hz, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 139.8, 132.6, 128.3, 128.1, 125.9, 125.2, 51.7, 38.5, 25.9; IR (neat): 3027,

2952, 2079, 1689, 1339; HRMS (APCI) calcd for $C_{13}H_{14}O_2N_2Na$ $(M+Na)^+$ 253.09475 found 253.09463.



methyl 2-diazo-5,5-diphenylpent-4-enoate (**4.19**)

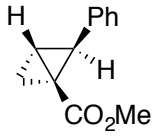
Prepared according to the general procedure for the synthesis of α-allyldiazoacetates using (3-bromoprop-1-ene-1,1-diyl)dibenzene (4.5 g, 16.5 mmol, 1.0 equiv) dissolved in anhydrous 1,2-dimethoxyethane (25 mL), ethyl acetoacetate (2.88 g, 24.8 mmol, 1.5 equiv) dissolved in anhydrous 1,2-dimethoxyethane (25 mL), sodium hydride (dry powder, 95%, 630 mg, 24.8 mmol, 1.5 equiv) dissolved in anhydrous 1,2-dimethoxyethane (20 mL) and *n*-Bu_4NI (608 mg, 1.65 mmol, 0.1 equiv). After general work up, the resulting α-allyl-β-ketoester was obtained and used without full characterization.

The resulting α-allyl-β-ketoester derivative (1.54 g, ca. 5.0 mmol, 1.0 equiv) was dissolved in dichloromethane (40 mL) and *p*-acetamidobenzenesulfonyl azide (*p*-ABSA) (2.4 g, 10 mmol, 2.0 equiv) was added at 0 °C under argon atmosphere. DBU (3.0 ml, 20 mmol, 4.0 equiv) was added drop-wise at 0 °C in 1.0 hour. The reaction mixture was then stirred for another 2.0 h. Then, 10% NaOH (15 mL) was added at 0 °C. The resulting mixture was warmed to room temperature. The crude α-allyldiazoester was extracted with dichloromethane (3 x 20 mL), washed by brine (3 x 10 mL), dried over anhydrous $MgSO_4$. Flash chromatographic purification (hexanes/ethyl acetate = 50/1) afforded the product (**4.19**) (890.8 mg, 61%) as a yellow oil.

^{1}H NMR (400 MHz, $CDCl_3$): δ 7.43-7.18 (m, 10H), 6.17 (t, *J* = 7.4 Hz, 1H), 3.77 (s, 3H), 3.15 (d, *J* = 7.4 Hz, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 144.9, 141.4, 138.8, 129.6, 128.3, 128.0, 127.4, 127.3, 127.1, 122.6, 51.8, 23.3; IR (neat): 3024, 2951, 2078, 2694, 1436, 341, 1190, 1116; HRMS (APCI) calcd for $C_{18}H_{17}O_2N_2$ $(M+H)^+$ 293.12848 found 293.12845.

General procedure for Rh_2(*R*-BTPCP)$_4$-catalyzed enantioselective synthesis of bicyclo[1.1.0]butane derivatives

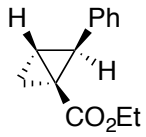
To a 25 mL flame-dried round-bottom flask, kept under a dry atmosphere of argon, was added dry ethyl acetate (1.0 mL) and Rh_2(*R*-BTPCP)$_4$ (0.1 mL, *c* = 0.70 mg/ mL in ethyl acetate, 0.0001 equiv). The diazo compound (0.4 mmol, 1.0 equiv), dissolved in dry ethyl acetate (2.0 mL), was then added to the former solution drop-wise over 0.5 hour at room temperature. The mixture was allowed to stir for another 15 min after the addition; when the diazo compound was fully consumed by TLC analysis, the reaction mixture was concentrated *in vacuo*. The crude residue was analyzed by ^{1}H NMR with C_6D_6 or freshly opened $CDCl_3$ kept under potassium carbonate as solvent and purified by flash column chromatography (hexanes/ethyl acetate) to afford the pure bicyclo[1.1.0]butane derivatives.



(1*S*,2*S*,3*R*)-methyl 2-phenylbicyclo[1.1.0]butane-1-carboxylate (**4.6**)

Prepared according to the general procedure for enantioselective synthesis of bicyclo[1.1.0]butane derivatives using (*E*)-methyl 2-diazo-5-phenylpent-4-enoate (**4.5**) (0.4 mmol, 86.4 mg, 1.0 equiv). The crude residue was analyzed by ^{1}H NMR and purified by flash column chromatography (hexanes/ethyl acetate = 50/1) to afford the product (**4.6**) as a colorless oil (52.4 mg, 70%).

$[\alpha]^{20}_{D}$ -38.1° (*c* = 1.81, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.32-7.23 (m, 3H), 7.17-7.15 (m, 2H), 3.55 (s, 3H), 2.75-2.74 (m, 1H), 2.39 (d, *J* = 1.2 Hz, 1H), 2.28 (d, *J* = 3.2 Hz, 1H), 1.14 (s, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 171.7, 134.6, 127.9, 127.2, 51.5, 50.5, 31.1, 19.8, 15.1; IR (neat): 2951, 1708, 1439, 1389, 1196, 1135; HRMS (APCI) calcd for $C_{12}H_{13}O_2$ $(M+H)^+$ 189.09101 found 189.09086; HPLC (S-250, 0% isopropanol in hexane, 1.0 mL/min, 1 mg/mL, 30 min, UV 210 nm) retention times of 15.7 min (minor) and 17.7 min (major), 94% ee.

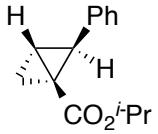


(1*S*,2*S*,3*R*)-ethyl 2-phenylbicyclo[1.1.0]butane-1-carboxylate (**4.17a**)

Prepared according to the general procedure for enantioselective synthesis of bicyclo[1.1.0]butane derivatives using (*E*)-ethyl 2-diazo-5-phenylpent-4-enoate (**4.16a**) (0.4 mmol, 92.0 mg, 1.0 equiv). The crude residue was analyzed by ^{1}H NMR and purified by flash column chromatography (hexanes/ethyl acetate = 50/1) to afford the product (**4.17a**) as a colorless oil (59.7 mg, 74%).

$[\alpha]^{20}_{D}$ -35.9° (*c* = 5.97, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.30-7.24 (m, 3H), 7.17-7.15 (m, 2H), 4.07-3.94 (m, 2H), 2.73-2.72 (m, 1H), 2.39 (d, *J* = 1.6 Hz, 1H), 2.29 (d, *J* =

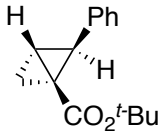
3.2 Hz, 1H), 1.13 (s, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 171.3, 134.8, 127.7, 127.2, 127.1, 60.2, 50.4, 31.0, 19.4, 15.4, 13.8; IR (neat): 2982, 1723, 1454, 1202; HRMS (APCI) calcd for $C_{13}H_{15}O_2$ $(M+H)^+$ 203.10666 found 203.10640; HPLC (S-250, 0% isopropanol in hexane, 1.0 mL/min, 1 mg/mL, 30 min, UV 210 nm) retention times of 11.5 min (minor) and 12.5 min (major), 94% ee.



(1*S*,2*S*,3*R*)-isopropyl 2-phenylbicyclo[1.1.0]butane-1-carboxylate (**4.17b**)

Prepared according to the general procedure for synthesis of bicyclo[1.1.0]butane derivatives using (*E*)-isopropyl 2-diazo-5-phenylpent-4-enoate (**4.16b**) (0.4 mmol, 97.6 mg, 1.0 equiv). The crude residue was analyzed by ^{1}H NMR and purified by flash column chromatography (hexanes/ethyl acetate = 50/1) to afford the product (**4.17b**) as a colorless oil (55.3 mg, 64%).

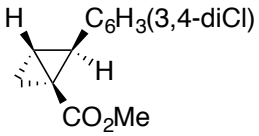
$[\alpha]^{20}_D$ -23.8° (*c* = 5.53, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.29-7.21 (m, 3H), 7.17-7.15 (m, 2H), 4.93-4.87 (m, 1H), 2.71-2.69 (m, 1H), 2.38 (d, *J* = 1.2 Hz, 1H), 2.28 (d, *J* = 1.2 Hz, 1H), 1.12 (s, 1H), 1.05 (d, *J* = 1.2 Hz, 1H), 1.08 (d, *J* = 6.2 Hz, 3H), 1.08 (d, *J* = 6.2 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 170.9, 134.9, 127.7, 127.3, 126.9, 67.6, 50.3, 31.0, 21.6, 21.2, 18.9, 15.8; IR (neat): 2979, 1703, 1404, 1208; HRMS (APCI) calcd for $C_{14}H_{17}O_2$ $(M+H)^+$ 217.12231 found 217.12202; HPLC (S-250, 0% isopropanol in hexane, 1.0 mL/min, 1 mg/mL, 30 min, UV 210 nm) retention times of 9.6 min (minor) and 10.3 min (major), 93% ee.



(1*S*,2*S*,3*R*)-*tert*-butyl 2-phenylbicyclo[1.1.0]butane-1-carboxylate (**4.17c**)

Prepared according to the general procedure for synthesis of bicyclo[1.1.0]butane derivatives using (*E*)-*tert*-butyl 2-diazo-5-phenylpent-4-enoate (**4.16c**) (0.4 mmol, 103.3 mg, 1.0 equiv). The crude residue was analyzed by ^{1}H NMR and purified by flash column chromatography (hexanes/ethyl acetate = 50/1) to afford the product (**4.17c**) as a colorless oil (41.7 mg, 45%).

$[\alpha]^{20}_{D}$ -16.3° (*c* = 4.16, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.29-7.22 (m, 3H), 7.16-7.14 (m, 2H), 2.68-2.66 (m, 1H), 2.34 (d, *J* = 1.2 Hz, 1H), 2.30 (d, *J* = 3.6 Hz, 1H), 1.18 (s, 9H), 1.07 (d, *J* = 1.4 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 170.6, 135.3, 127.7, 127.2, 126.9, 80.4, 50.1, 30.2, 27.6, 18.6, 16.8; IR (neat): 2976, 1699, 1394, 1221; HRMS (APCI) calcd for $C_{15}H_{19}O_2$ $(M+H)^+$ 231.13796 found 231.13770; HPLC (S,S-Whelk, 0.5% isopropanol in hexane, 1.0 mL/min, 1 mg/mL, 30 min, UV 230 nm) retention times of 6.2 min (minor) and 7.2 min (major), 70% ee.

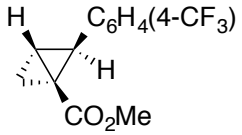


(1*S*,2*S*,3*R*)-methyl 2-(3,4-dichlorophenyl)bicyclo[1.1.0]butane-1-carboxylate (**4.17d**)

Prepared according to the general procedure for synthesis of bicyclo[1.1.0]butane derivatives using (*E*)-methyl 2-diazo-5-(3,4-dichlorophenyl)pent-4-enoate (**4.16d**) (0.4 mmol, 113.6 mg, 1.0 equiv). The crude residue was analyzed by ^{1}H NMR and purified by

flash column chromatography (hexanes/ethyl acetate = 50/1) to afford the product (**4.17d**) as a colorless oil (66.3 mg, 65%).

$[\alpha]^{20}_{D}$ -38.2 ° (*c* = 3.73, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.33 (d, *J* = 8.3 Hz, 1H), 7.23 (d, *J* = 2.1 Hz, 1H), 6.97 (dd, *J* = 2.1, 8.3 Hz, 1H), 3.56 (s, 3H), 2.74-2.72 (m, 1H), 2.29-2.25 (m, 2H), 1.11 (s, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 171.1, 134.9, 131.1, 129.8, 129.3, 126.6, 51.6, 48.9, 30.8, 19.7, 13.3; IR (neat): 2951, 1712, 1474, 1439, 1199, 1134; HRMS (APCI) calcd for $C_{12}H_{11}O_2Cl_2$ $(M+H)^+$ 257.01306 found 257.01279; HPLC (S-250, 0% isopropanol in hexane, 1.0 mL/min, 1 mg/mL, 30 min, UV 210 nm) retention times of 14.0 min (minor) and 18.0 min (major), 90% ee.

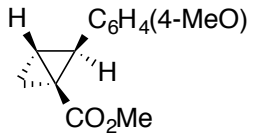


(1*S*,2*S*,3*R*)-methyl 2-(4-(trifluoromethyl)phenyl)bicyclo[1.1.0]butane-1-carboxylate (**4.17e**)

Prepared according to the general procedure for synthesis of bicyclo[1.1.0]butane derivatives using (*E*)-methyl 2-diazo-5-(4-(trifluoromethyl)phenyl)pent-4-enoate (**4.16e**) (0.4 mmol, 113.6 mg, 1.0 equiv). The crude residue was analyzed by ^{1}H NMR and purified by flash column chromatography (hexanes/ethyl acetate = 50/1) to afford the product (**4.17e**) as a colorless oil (64.6 mg, 63%).

$[\alpha]^{20}_{D}$ -11.4° (*c* = 1.10, $CHCl_3$); ^{1}H NMR (400 MHz, C_6D_6): δ 7.30 (d, *J* = 8.4 Hz, 2H), 6.78 (d, *J* = 8.4 Hz, 2H), 3.19 (s, 3H), 2.20-2.18 (m, 1H), 2.11 (app. dd, *J* = 0.8, 3.2 Hz, 1H), 1.90 (d, *J* = 1.6 Hz, 1H), 0.77-0.76 (m, 1H); ^{13}C NMR (100 MHz, C_6D_6) δ 170.1, 139.2, 131.1, 128.2, 127.9, 127.7, 124.8 (q), 51.0, 49.5, 30.8, 19.4, 15.7; IR (neat): 2955, 1716, 1620, 1326, 1121, 1068; HRMS (APCI) calcd for $C_{13}H_{12}O_2F_3$ $(M+H)^+$ 257.07839

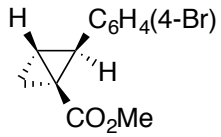
found 257.07791; HPLC (S-250, 0% isopropanol in hexane, 1.0 mL/min, 1 mg/mL, 60 min, UV 210 nm) retention times of 45.6 min (minor) and 48.3 min (major), 94% ee.



(1*S*,2*S*,3*R*)-methyl 2-(4-methoxyphenyl)bicyclo[1.1.0]butane-1-carboxylate (**4.17f**)

Prepared according to the general procedure for Rh_2(*R*-BTPCP)$_4$-catalyzed synthesis of bicyclo[1.1.0]butane derivatives using (*E*)-methyl 2-diazo-5-(4-methoxyphenyl)pent-4-enoate (**4.16f**) (0.4 mmol, 98.4 mg, 1.0 equiv). The crude residue was analyzed by ^{1}H NMR and purified by flash column chromatography (hexanes/ethyl acetate = 50/1) to afford the product (**4.17f**) as a colorless oil (57.4 mg, 66%).

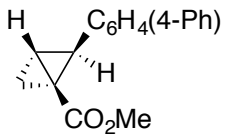
$[\alpha]^{20}_D$ -30.1° (*c* = 1.10, $CHCl_3$); ^{1}H NMR (400 MHz, C_6D_6): δ 7.10 (d, *J* = 8.8 Hz, 2H), 6.85 (d, *J* = 8.8 Hz, 2H), 3.81 (s, 3H), 3.59 (s, 3H), 2.69-2.68 (m, 1H), 2.38 (d, *J* = 1.6 Hz, 1H), 2.28 (app. dd, *J* = 1.2, 3.6 Hz, 1H), 1.29 (s, 1H); ^{13}C NMR (100 MHz, C_6D_6) δ 171.9, 158.7, 128.2, 126.8, 113.3, 55.2, 51.5, 50.2, 30.9, 19.8, 14.8; IR (neat): 2952, 2836, 1706, 1516, 1439, 1038; HRMS (APCI) calcd for $C_{13}H_{15}O_3$ $(M+H)^+$ 219.10157 found 219.10144; HPLC (ADH, 1.0 % isopropanol in hexane, 1.0 mL/min, 1 mg/mL, 30 min, UV 230 nm) retention times of 19.8 min (minor) and 20.8 min (major), 85% ee.



(1*S*,2*S*,3*R*)-methyl 2-(4-bromophenyl)bicyclo[1.1.0]butane-1-carboxylate (**4.17g**)

Prepared according to the general procedure for Rh_2(*R*-BTPCP)$_4$-catalyzed synthesis of bicyclo[1.1.0]butane derivatives using (*E*)-methyl 5-(4-bromophenyl)-2-diazopent-4-enoate (**4.16g**) (0.4 mmol, 117.6 mg, 1.0 equiv). The crude residue was analyzed by ^{1}H NMR and purified by flash column chromatography (hexanes/ethyl acetate = 50/1) to afford the product (**4.17g**) as a colorless oil (70.4 mg, 66%).

$[\alpha]^{20}_D$ -30.4° (*c* = 3.13, $CHCl_3$); ^{1}H NMR (400 MHz, C_6D_6): δ 7.42 (d, *J* = 8.4 Hz, 2H), 7.05 (d, *J* = 8.4 Hz, 2H), 3.58 (s, 3H), 2.35 (d, *J* = 1.6 Hz, 1H), 2.29 (app. dd, *J* = 1.2, 3.6 Hz, 1H), 1.15 (s, 1H); ^{13}C NMR (100 MHz, C_6D_6) δ 171.4, 133.7, 130.9, 128.9, 121.1, 51.6, 49.7, 30.9, 19.7, 15.2; IR (neat): 2949, 1709, 1207, 1135; HRMS (APCI) calcd for $C_{12}H_{12}O_2Br$ $(M+H)^+$ 267.00152 found 267.00189; HPLC (S250, 0 % isopropanol in hexane, 1.0 mL/min, 1 mg/mL, 30 min, UV 230 nm) retention times of 16.3 min (minor) and 18.9 min (major), 93% ee.

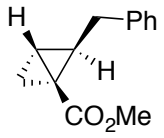


(1*S*,2*S*,3*R*)-methyl 2-([1,1'-biphenyl]-4-yl)bicyclo[1.1.0]butane-1-carboxylate (**4.17h**)

Prepared according to the general procedure for synthesis of bicyclo[1.1.0]butane derivatives using (*E*)-methyl 5-(4-bromophenyl)-2-diazopent-4-enoate (**4.16h**) (0.4 mmol, 116.8 mg, 1.0 equiv). The crude residue was analyzed by ^{1}H NMR and purified by flash column chromatography (hexanes/ethyl acetate = 50/1) to afford the product (**4.17h**) as a white solid (64.3 mg, 61%).

Mp; 99-101 °C; $[\alpha]^{20}_D$ -37.4° (*c* = 1.17, CH_3CN); ^{1}H NMR (400 MHz, C_6D_6): δ 7.60-7.58 (m, 2H), 7.53 (d, *J* = 8.4 Hz, 2H), 745-7.41 (m, 2H), 7.35-7.33 (m, 1H), 7.26-7.25 (m,

2H), 3.60 (s, 3H), 2.80-2.79 (m, 1H), 2.45 (app. d, J = 1.2 Hz, 1H), 2.32 (app. dd, J = 1.2, 4.2 Hz, 1H), 1.18 (s, 1H); ^{13}C NMR (100 MHz, C_6D_6) δ 171.7, 140.8, 140.0, 133.7, 128.7, 127.7, 127.2, 126.9, 126.6, 51.6, 50.3, 31.1, 20.1, 15.2; IR (neat): 3030, 2949, 1712, 1207, 1135; HRMS (APCI) calcd for $C_{18}H_{17}O_2$ $(M+H)^+$ 265.12231 found 265.12283; HPLC (ODH, 0.5% isopropanol in hexane, 0.5 mL/min, 1 mg/mL, 60 min, UV 230 nm) retention times of 16.5 min (minor) and 41.8 min (major), 91% ee.



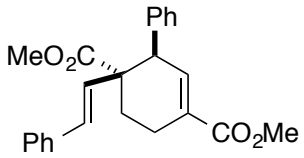
(1*S*,2*S*,3*R*)-methyl 2-([1,1'-biphenyl]-4-yl)bicyclo[1.1.0]butane-1-carboxylate (**4.17i**)

Prepared according to the general procedure for synthesis of bicyclo[1.1.0]butane derivatives using (*E*)-methyl 2-diazo-6-phenylhex-4-enoate (**4.16i**) (0.4 mmol, 92.0 mg, 1.0 equiv). The crude residue was analyzed by ^{1}H NMR and purified by flash column chromatography (hexanes/ethyl acetate = 50/1) to afford the product (**4.17i**) as a colorless oil (59.4 mg, 74%).

$[\alpha]^{20}_D$ -6.8° (c = 2.43, $CHCl_3$); ^{1}H NMR (400 MHz, C_6D_6): δ 7.33-7.21 (m, 5H), 3.73 (s, 3H), 3.26 (dd, J = 4.4, 15.0 Hz, 1H), 2.83 (dd, J = 8.0, 15.0 Hz, 1H), 2.29 (s, 2H), 1.64-1.60 (m, 1H), 1.05 (s, 1H); ^{13}C NMR (100 MHz, C_6D_6) δ 173.1, 140.4, 128.3, 126.1, 51.6, 49.7, 34.0, 32.9, 21.3, 12.4; IR (neat): 2952, 1713, 1209, 1128; HRMS (APCI) calcd for $C_{13}H_{14}O_2Na$ $(M+Na)^+$ 225.08860 found 225.08834; HPLC (ODR, 0.25% isopropanol in hexane, 1.0 mL/min, 1 mg/mL, 30 min, UV 230 nm) retention times of 5.9 min (minor) and 6.5 min (major), 51% ee.

General procedure for $Rh_2(TPA)_4$-catalyzed synthesis of cyclohexene derivatives

To a 25 mL flame-dried round-bottom flask, kept under a dry atmosphere of argon, was added dry and degassed hexane (1.0 mL) and $Rh_2(TPA)_4$ (5.4 mg, 0.01 equiv). The diazo compound (0.4 mmol, 1.0 equiv), dissolved in dry and degassed hexane (2.0 mL), was then added to the former solution drop-wise over 0.5 hour at room temperature. The mixture was allowed to stir for another 12-48 hours after the addition. Then, the reaction mixture was concentrated *in vacuo*. The crude residue was analyzed by ^{1}H NMR with C_6D_6 or freshly opened $CDCl_3$, which was kept under potassium carbonate, as solvent and purified by flash column chromatography (hexanes/ethyl acetate) to afford the pure cyclohexene derivatives.

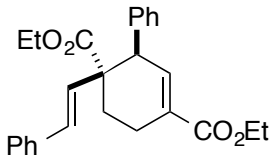


(1*R*,2*R*)-dimethyl 2-((*E*)-styryl)-1,2,3,4-tetrahydro-[1,1'-biphenyl]-2,5-dicarboxylate (**4.15**)

Prepared according to the general procedure for $Rh_2(TPA)_4$-catalyzed synthesis of cyclohexene derivatives using (*E*)-methyl 2-diazo-4-methyl-5-phenylpent-4-enoate (**4.5**) (0.4 mmol, 86.4 mg, 1.0 equiv). The crude residue was analyzed by ^{1}H NMR and purified by flash column chromatography (hexanes/ethyl acetate = 50/1) to afford the product (**4.15**) as an amorphous solid (60.1 mg, 80%).

^{1}H NMR (400 MHz, $CDCl_3$): δ 7.26-7.09 (m, 10H), 7.05 (d, J = 5.2 Hz, 1H), 6.18 (d, J = 16.6 Hz, 1H), 5.74 (d, J = 16.6 Hz, 1H), 4.40 (d, J = 5.2 Hz, 1H), 3.74 (s, 3H), 2.63 (dd, J

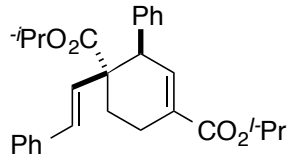
= 5.8, 18.6 Hz, 1H), 2.50-2.46 (m, 1H), 1.89 (ddd, *J* = 6.4, 10.8, 13.6 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 174.6, 167.4, 139.5, 138.0, 136.8, 131.4, 130.6, 129.9, 129.5, 128.4, 127.9, 127.5, 127.3, 126.2, 52.5, 51.7, 51.3, 47.7, 24.5, 22.2; IR (neat): 3026, 2949, 1712, 1435, 1256, 1229; HRMS (APCI) calcd for $C_{24}H_{25}O_4$ $(M+H)^+$ 377.17474 found 377.17493.



(1*R*,2*R*)-diethyl 2-((*E*)-styryl)-1,2,3,4-tetrahydro-[1,1'-biphenyl]-2,5-dicarboxylate (**4.18a**)

Prepared according to the general procedure for $Rh_2(TPA)_4$-catalyzed synthesis of cyclohexene derivatives using (*E*)-ethyl 2-diazo-5-phenylpent-4-enoate (**4.16a**) (0.4 mmol, 92 mg, 1.0 equiv). The crude residue was analyzed by ^{1}H NMR and purified by flash column chromatography (hexanes/ethyl acetate = 50/1) to afford the product (**4.18a**) as a white solid (65.7 mg, 81%).

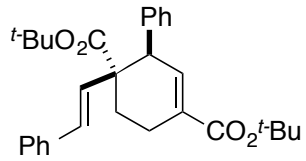
Mp: 101-103 °C ; ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.24-7.06 (m, 10H), 6.21 (d, *J* = 16.4 Hz, 1H), 5.73 (d, *J* = 16.4 Hz, 1H), 4.41 (d, *J* = 5.1 Hz, 1H), 4.24-4.16 (m, 4H), 2.64 (dd, *J* = 5.7, 18.8 Hz, 1H), 2.52-2.43 (m, 1H), 2.31 (dd, *J* = 6.4, 13.7 Hz, 1H), 1.89 (ddd, *J* = 6.4, 10.8, 13.6 Hz, 1H), 1.27 (q, *J* = 7.0 Hz, 6H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 174.1, 166.9, 139.3, 138.2, 136.8, 131.7, 130.7, 130.1, 129.4, 128.4, 127.9, 127.4, 127.2, 126.2, 61.2, 60.5, 51.1, 47.6, 24.5, 22.1, 14.2; IR (neat): 3027, 2979, 1716, 1255, 1229, 1088; HRMS (APCI) calcd for $C_{26}H_{29}O_4$ $(M+H)^+$ 405.20604 found 405.20536.



(1*R*,2*R*)-diisopropyl 2-((*E*)-styryl)-1,2,3,4-tetrahydro-[1,1'-biphenyl]-2,5-dicarboxylate (**4.18b**)

Prepared according to the general procedure for $Rh_2(TPA)_4$-catalyzed synthesis of cyclohexene derivatives using (*E*)-isopropyl 2-diazo-5-phenylpent-4-enoate (**4.16b**) (0.4 mmol, 97.6 mg, 1.0 equiv). The crude residue was analyzed by ^{1}H NMR and purified by flash column chromatography (hexanes/ethyl acetate = 50/1) to afford the product (**4.18b**) as a white solid (39.5 mg, 46%).

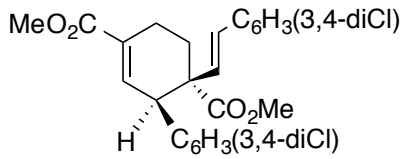
Mp: 133-135 °C ; ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.28-7.10 (m, 10H), 7.04 (d, *J* = 5.4 Hz, 1H), 6.23 (d, *J* = 16.6 Hz, 1H), 5.70 (d, *J* = 16.6 Hz, 1H), 5.14-5.06 (m, 2H), 4.40 (d, *J* = 5.4 Hz, 1H), 2.63 (dd, *J* = 6.6, 19.2 Hz, 1H), 2.61-2.44 (m, 1H), 2.29 (dd, *J* = 6.6, 13.8 Hz, 1H), 1.90-1.85 (m, 1H), 1.28-1.24 (m, 12H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 173.5, 166.5, 139.1, 138.3, 136.9, 132.0, 130.7, 130.4, 129.4, 128.4, 127.9, 127.4, 127.2, 126.2, 68.6, 67.8, 51.1, 47.6, 24.6, 22.1, 21.9, 21.7, 21.6; IR (neat): 2979, 2936, 1710, 1452, 1106; HRMS (APCI) calcd for $C_{28}H_{33}O_4$ $(M+H)^+$ 433.23734 found 433.23679.



(1*R*,2*R*)-di-*tert*-butyl 2-((*E*)-styryl)-1,2,3,4-tetrahydro-[1,1'-biphenyl]-2,5-dicarboxylate (**4.18c**)

Prepared according to the general procedure for $Rh_2(TPA)_4$-catalyzed synthesis of cyclohexene derivatives using (*E*)-tert-butyl 2-diazo-5-phenylpent-4-enoate (**4.16c**) (0.4 mmol, 103.3 mg, 1.0 equiv). The crude residue was analyzed by ^{1}H NMR and purified by flash column chromatography (hexanes/ethyl acetate = 50/1) to afford the product (**4.18c**) as an amorphous white solid (17.6 mg, 20%).

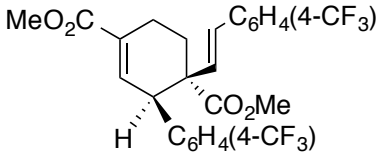
^{1}H NMR (400 MHz, $CDCl_3$): δ 7.27-7.07 (m, 10H), 6.94 (d, *J* = 5.4 Hz, 1H), 6.23 (d, *J* = 16.4 Hz, 1H), 5.67 (d, *J* = 16.4 Hz, 1H), 4.30 (d, *J* = 5.2 Hz, 1H), 2.55 (dd, *J* = 6.2, 18.1 Hz, 1H), 2.48-2.39 (m, 1H), 2.22-2.17 (m, 1H), 1.79 (ddd, *J* = 6.6, 10.7, 13.6 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 173.2, 166.4, 138.6, 137.1, 132.4, 131.5, 130.8, 129.1, 128.4, 127.8, 127.3, 127.1, 126.2, 81.3, 80.3, 51.6, 47.4, 28.1, 27.9, 24.8, 22.2; IR (neat): 2976, 2931, 1705, 1367, 1155; HRMS (APCI) calcd for $C_{30}H_{35}O_4$ $(M-H)^+$ 459.25408 found 459.25464.



(1*R*,2*R*)-dimethyl 3',4'-dichloro-2-((*E*)-3,4-dichlorostyryl)-1,2,3,4-tetrahydro-[1,1'-biphenyl]-2,5-dicarboxylate (**4.18d**)

Prepared according to the general procedure for $Rh_2(TPA)_4$-catalyzed synthesis of cyclohexene derivatives using (*E*)-methyl 2-diazo-5-(3,4-dichlorophenyl)pent-4-enoate (**4.16d**) (0.4 mmol, 113.6 mg, 1.0 equiv). The crude residue was analyzed by ^{1}H NMR and purified by flash column chromatography (hexanes/ethyl acetate = 50/1) to afford the product (**4.18d**) as an amorphous white solid (87.4 mg, 85%).

^{1}H NMR (400 MHz, $CDCl_3$): δ 7.30 (dd, *J* = 3.6, 8.4 Hz, 2H), 7.18 (dd, *J* = 2.0, 10.4 Hz, 2H), 6.94 (app. dd, *J* = 2.0, 6.8 Hz, 2H), 6.91 (d, *J* = 2.0 Hz, 1H), 6.11 (d, *J* = 16.4 Hz, 1H), 5.73 (d, *J* = 16.4 Hz, 1H), 4.34 (d, *J* = 4.8 Hz, 1H), 3.75 (s, 3H), 3.73 (s, 3H), 2.63 (app. dd, *J* = 6.0, 19.2 Hz, 1H), 2.48-2.39 (m, 1H), 2.29 (app. dd, *J* = 6.4, 14.0 Hz, 1H), 1.78 (ddd, *J* = 6.4, 10.4, 13.6 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 173.2, 166.9, 138.3, 137.8, 136.4, 132.5, 132.2, 132.1, 130.9, 130.5, 129.8, 128.2, 128.1, 125.3, 52.8, 51.9, 51.2, 46.7, 24.3, 22.0; IR (neat): 2950, 1720, 1470, 1255; HRMS (APCI) calcd for $C_{24}H_{21}O_4Cl_4$ $(M+H)^+$ 513.01885 found 513.01874.

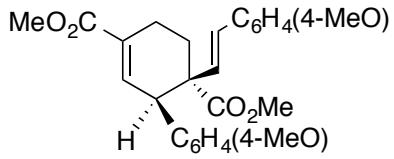


(1*R*,2*R*)-dimethyl 4'-(trifluoromethyl)-2-((*E*)-4-(trifluoromethyl)styryl)-1,2,3,4-tetrahydro-[1,1'-biphenyl]-2,5-dicarboxylate (**4.18e**)

Prepared according to the general procedure for $Rh_2(TPA)_4$-catalyzed synthesis of cyclohexene derivatives using (*E*)-methyl 2-diazo-5-(4-(trifluoromethyl)phenyl)pent-4-enoate (**4.16e**) (0.4 mmol, 113.6 mg, 1.0 equiv). The crude residue was analyzed by ^{1}H NMR and purified by flash column chromatography (hexanes/ethyl acetate = 50/1) to afford the product (**4.18e**) as an amorphous white solid (91.3 mg, 89%).

^{1}H NMR (400 MHz, $CDCl_3$): δ 7.50 (dd, *J* = 8.4, 12.4 Hz, 4H), 7.23 (d, *J* = 8.2 Hz, 2H), 7.18 (d, *J* = 8.2 Hz, 2H), 7.0 (d, *J* = 5.2 Hz, 1H), 6.22 (d, *J* = 16.6 Hz, 1H), 5.80 (d, *J* = 16.6 Hz, 1H), 4.47 (d, *J* = 4.8 Hz, 1H), 3.76 (s, 3H), 3.75 (s, 3H), 2.70 (dd, *J* = 5.6, 18.9 Hz, 1H), 2.53-2.50 (m, 1H), 2.36 (dd, *J* = 5.8, 13.8 Hz, 1H), 1.89 (ddd, *J* = 6.3, 12.1, 13.8 Hz, 1H); ^{19}F NMR (376 MHz, $CDCl_3$) δ -63.0; ^{13}C NMR (100 MHz, $CDCl_3$) δ 173.9,

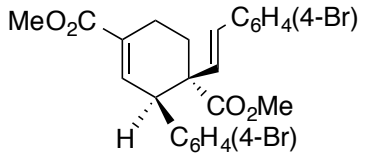
167.1, 142.2, 139.8, 138.2, 133.2, 130.9, 130.8, 129.1, 126.4, 125.6, 125.5, 124.9, 52.8, 51.9, 51.3, 47.4, 24.6, 22.1; IR (neat): 2953, 1723, 1325, 1124; HRMS (ESI) calcd for $C_{26}H_{23}O_4F_6$ $(M+H)^+$ 513.14951 found 513.15025.



(1*R*,2*R*)-dimethyl 4'-methoxy-2-((*E*)-4-methoxystyryl)-1,2,3,4-tetrahydro-[1,1'-biphenyl]-2,5-dicarboxylate (**4.18f**)

Prepared according to the general procedure for $Rh_2(TPA)_4$-catalyzed synthesis of cyclohexene derivatives using (*E*)-methyl 2-diazo-5-(4-methoxyphenyl)pent-4-enoate (**4.16f**) (0.4 mmol, 98.4 mg, 1.0 equiv). The crude residue was analyzed by ^{1}H NMR and purified by flash column chromatography (hexanes/ethyl acetate = 50/1) to afford the product (**4.18f**) as an amorphous white solid (72.6 mg, 83%).

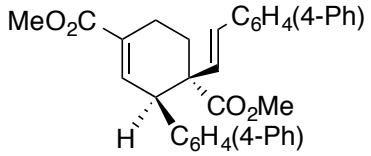
^{1}H NMR (400 MHz, $CDCl_3$): δ 7.08-7.01 (m, 5H), 6.81-6.74 (m, 4H), 6.12 (d, *J* = 16.4 Hz, 1H), 5.60 (d, *J* = 16.4 Hz, 1H), 4.32 (d, *J* = 4.4 Hz, 1H), 3.75 -3.73 (m, 12H), 2.60 (app. dd, *J* = 5.6, 18.8 Hz, 1H), 2.47-2.40 (m, 1H), 2.27 (app. dd, *J* = 4.8, 13.6 Hz, 1H), 1.84 (ddd, *J* = 6.4, 10.8, 13.2 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 175.1, 167.7, 159.4, 158.9, 140.2, 131.9, 130.3, 129.8, 129.7, 129.1, 127.6, 114.1, 113.5, 55.5, 55.4, 52.6, 51.9, 51.5, 47.2, 24.8, 22.4; IR (neat): 2950, 2837, 1713, 1510, 1245; HRMS (APCI) calcd for $C_{26}H_{29}O_6$ $(M+H)^+$ 437.19587 found 437.19653.



(1*R*,2*R*)-dimethyl 4'-bromo-2-((*E*)-4-bromostyryl)-1,2,3,4-tetrahydro-[1,1'-biphenyl]-2,5-dicarboxylate (**4.18g**)

Prepared according to the general procedure for $Rh_2(TPA)_4$-catalyzed synthesis of cyclohexene derivatives using (*E*)-methyl 5-(4-bromophenyl)-2-diazopent-4-enoate (**4.16g**) (0.4 mmol, 117.6 mg, 1.0 equiv). The crude residue was analyzed by ^{1}H NMR and purified by flash column chromatography (hexanes/ethyl acetate = 50/1) to afford the product (**4.18g**) as an amorphous solid (86.9 mg, 82%).

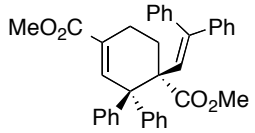
^{1}H NMR (400 MHz, $CDCl_3$): δ 7.40-7.37 (m, 4H), 7.01-6.98 (m, 5H), 6.13 (d, *J* = 16.0 Hz, 1H), 5.73 (d, *J* = 16.0 Hz, 1H), 4.36 (d, *J* = 4.8 Hz, 1H), 3.76 (s, 6H), 2.63 (app. dd, *J* = 5.6, 18.8 Hz, 1H), 2.51-2.42 (m, 1H), 2.31 (app. dd, *J* = 6.4, 14.0 Hz, 1H), 1.84 (ddd, *J* = 6.0, 10.4, 13.2 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 174.2, 167.1, 138.7, 137.0, 135.4, 132.2, 131.6, 131.1, 130.3, 128.9, 127.7, 121.5, 52.6, 51.8, 51.2, 47.1, 24.4, 22.1; IR (neat): 2949, 1716, 1487, 1258, 1229; HRMS (APCI) calcd for $C_{24}H_{22}O_4Br_2Cl$ $(M+Cl)^+$ 566.95788 found 566.95802.



(1*R*,2*R*)-dimethyl 2-((*E*)-2-([1,1'-biphenyl]-4-yl)vinyl)-1,2,3,4-tetrahydro-[1,1':4',1''-terphenyl]-2,5-dicarboxylate (**4.18h**)

Prepared according to the general procedure for $Rh_2(TPA)_4$-catalyzed synthesis of cyclohexene derivatives using (*E*)-4-(3-bromoprop-1-en-1-yl)-1,1'-biphenyl (**4.16h**) (0.4 mmol, 116.8 mg, 1.0 equiv). The crude residue was analyzed by ^{1}H NMR and purified by flash column chromatography (hexanes/ethyl acetate = 50/1) to afford the product (**4.18h**) as a white solid (87.4 mg, 83%).

Mp: 73-75 °C; ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.49-7.39 (m, 8H), 7.36-7.32 (m, 4H), 7.27-7.23 (m, 2H), 7.17-7.13 (m, 4H), 7.02 (d, *J* = 5.2 Hz, 1H), 6.20 (d, *J* = 16.4 Hz, 1H), 5.78 (d, *J* = 16.4 Hz, 1H), 4.40 (d, *J* = 5.2 Hz, 1H), 3.70 (s, 6H), 2.60 (app. dd, *J* = 4.8, 18.0 Hz, 1H), 2.47-2.38 (m, 1H), 2.28 (app. dd, *J* = 6.0, 13.2 Hz, 1H), 1.89 (ddd, *J* = 6.4, 10.8, 14.0 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 174.6, 167.4, 140.6, 140.5, 140.3, 140.1, 139.5, 137.1, 135.7, 131.4, 131.1, 130.0, 129.3, 128.7, 127.3, 127.2, 127.0, 126.9, 126.7, 126.6, 52.5, 51.8, 51.4, 47.4, 24.7, 22.2; IR (neat): 3027, 2949, 1723, 1258, 1231; HRMS (APCI) calcd for $C_{36}H_{33}O_4$ $(M+H)^+$ 529.23734 found 529.23773.



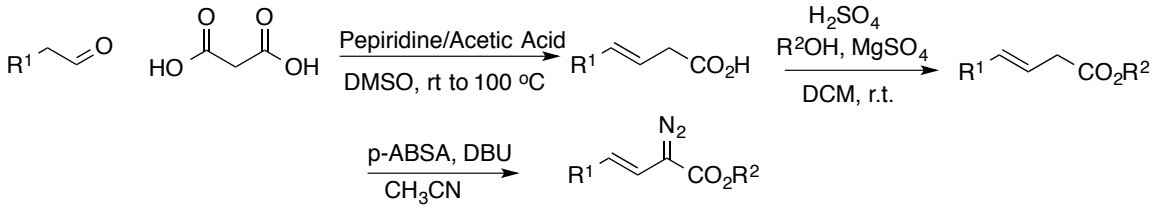
(*R*)-dimethyl 2'-(2,2-diphenylvinyl)-3',4'-dihydro-2'*H*-[1,1':1',1"-terphenyl]-2',5'-dicarboxylate (**4.21**)

Prepared according to the general procedure for $Rh_2(TPA)_4$-catalyzed synthesis of bicyclo[1.1.0]butane derivatives using methyl 2-diazo-5,5-diphenylpent-4-enoate (**4.19**) (0.4 mmol, 116.8 mg, 1.0 equiv). The crude residue was analyzed by ^{1}H NMR and purified by flash column chromatography (hexanes/ethyl acetate = 50/1) to afford the product (**4.21**) as an amorphous solid (67.2 mg, 64%).

^{1}H NMR (400 MHz, $CDCl_3$): δ 7.93 (d, J = 7.6 Hz, 2H), 7.29-7.08 (m, 20H), 6.92-6.89 (m, 2H), 6.52 (s, 2H), 3.75 (s, 3H), 2.81 (s, 3H), 2.51-2.43 (m, 2H), 2.13-2.01 (m, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 172.8, 167.3, 145.2, 144.7, 144.6, 142.9, 141.1, 138.6, 131.9, 131.1, 130.3, 130.1, 128.2, 127.8, 127.4, 127.2, 126.9, 126.8, 126.2, 60.1, 54.3, 51.9, 51.0, 50.9, 29.2, 21.9; IR (neat): 3055, 3022, 2948, 1716; HRMS (APCI) calcd for $C_{36}H_{33}O_4$ $(M+H)^+$ 529.23734, found 529.23750.

Experimental Data for Chapter V:

General procedure for the synthesis of new vinyl diazoacetates for formal [3+2]-annulation

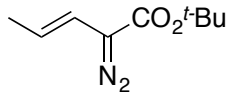


In a 1.0 liter round bottomed flask, equipped with a condenser and a bubbler connected to the exit of the condenser, filled with the reaction solvent, a solution of malonic acid (1.0 mol, 104 g, 2.0 equiv), piperidinium acetate (from 0.85 g of piperidine and 0.6 g of acetic acid, 0.01 mol), and aldehyde illustrated by propionaldehyde (0.5 mol, 29.0 g, 1.0 equiv), in DMSO (400 mL), was stirred under argon at room temperature for 20 min. Then, the argon was removed and the solution was heated on an oil bath at 100 ^{o}C. A rapid evolution of carbon dioxide was observed. Heating was maintained until the evolution of carbon dioxide was ceased. The solution was cooled to room temperature, poured into 1.0 liter of cold water and extracted with diethyl ether (3 x 300 mL). The combined extracts were washed with brine (3 x 100 mL), dried over anhydrous $MgSO_4$ and evaporated

under reduced pressure. The crude product was pure enough and used without further purification in the next esterification step.

In a round-bottomed flask was charged with anhydrous $MgSO_4$ (4.0 equiv) in the given volume of dichloromethane solution, sulfuric acid (1.0 equiv) was added and the mixture was stirred for 0.5 hour at room temperature. Then, the carboxylic acid (1.0 equiv) obtained from above procedure and the given alcohol (5.0 equiv) was added subsequently. The resulting mixture went overnight 12 hours or more depending on the scale of the reaction. The reaction was filtered and the solution was neutralized with saturated sodium bicarbonate and washed by brine, dried over anhydrous $MgSO_4$ and evaporated under reduced pressure. The crude product was pure enough and used without any purification in the next diazo transfer step, or a short column purification if needed.

To a stirred solution of the ester obtained previously (1.0 equiv) and *p*-acetamidobenzenesulfonyl azide (*p*-ABSA) (5.0 equiv) in acetonitrile, DBU (8.0 equiv) was added drop-wise at 0 °C. The reaction mixture was then stirred overnight. Then, saturated aqueous ammonium chloride was added. The crude mixture was extracted with pentane, washed by brine, dried over anhydrous $MgSO_4$, concentrated *in vacuo*, and chromatographed (pentane/diethyl ether) to afford the vinyl diazoacetates.

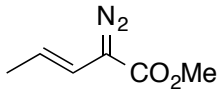


(*E*)-*tert*-butyl 2-diazopent-3-enoate (**5.36**)

Prepared according to the general procedure for the synthesis of vinyl diazoacetates. To a stirred solution of crude (*E*)-*tert*-butyl pent-3-enoate (ca. 760 mg, ca. 5.0 mmol, 1.0 equiv) and *p*-acetamidobenzenesulfonyl azide (*p*-ABSA) (6.0 g, 25 mmol, 5.0 equiv) in

acetonitrile (50 mL), DBU (6.0 mL, 40 mmol, 8.0 equiv) was added drop-wise at 0 °C. The reaction mixture was then stirred overnight. Then, saturated aqueous ammonium chloride (10 mL) was added. The crude mixture was extracted with pentane (3 x 50 mL), washed by brine (3 x 10 mL), dried over anhydrous $MgSO_4$, concentrated *in vacuo*, and chromatographed (pentane/diethyl ether = 50/1) to afford the (*E*)-isopropyl 2-diazopent-3-enoate (**5.36**) (418.6 mg, 46%) as an orange oil.

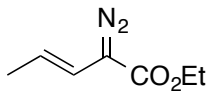
^{1}H NMR (400 MHz, $CDCl_3$): δ 5.72-5.67 (m, 1H), 5.32-5.25 (m, 1H), 1.84-1.81 (m, 3H), 1.48 (s, 9H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 164.9, 119.7, 113.1, 81.7, 28.3, 18.2; IR (neat): 2977, 2076, 1709, 1368, 1151; HRMS (APCI) calcd for $C_9H_{15}O_2N_2$ $(M+H)^+$ 183.11280 found 183.11255.



(*E*)-methyl 2-diazopent-3-enoate (**5.23**)

Prepared according to the general procedure for the synthesis of vinyl diazoacetates. To a stirred solution of crude (*E*)-methyl pent-3-enoate (ca. 570 mg, ca. 5.0 mmol, 1.0 equiv) and *p*-acetamidobenzenesulfonyl azide (*p*-ABSA) (6.0 g, 25 mmol, 5.0 equiv) in acetonitrile (50 mL), DBU (6.0 mL, 40 mmol, 8.0 equiv) was added dropwise at 0 °C. The reaction mixture was then stirred overnight. Then, saturated aqueous ammonium chloride (10 mL) was added. The crude mixture was extracted with pentane (3 x 50 mL), washed by brine (3 x 10 mL), dried over anhydrous $MgSO_4$, concentrated *in vacuo*, and chromatographed (pentane/diethyl ether = 50/1) to afford the (*E*)-methyl 2-diazopent-3-enoate (**5.23**) (294 mg, 42%) as an orange oil.

^{1}H NMR (400 MHz, $CDCl_3$): δ 5.77-5.72 (m, 1H), 5.37-5.31 (m, 1H), 3.81 (s, 3H), 1.86-1.84 (m, 3H). The NMR spectral data are consistent with previously reported results.[18]



(*E*)-ethyl 2-diazopent-3-enoate (**5.36a**)

Prepared according to the general procedure for the synthesis of vinyl diazoacetates. To a stirred solution of crude (*E*)-ethyl pent-3-enoate (640 mg, 5.0 mmol, 1.0 equiv) and *p*-acetamidobenzenesulfonyl azide (*p*-ABSA) (6.0 g, 25 mmol, 5.0 equiv) in acetonitrile, DBU (6.0 mL, 40 mmol, 8.0 equiv) was added drop-wise at 0 °C. The reaction mixture was then stirred overnight. Then, saturated aqueous ammonium chloride (10 mL) was added. The crude mixture was extracted with pentane (3 x 50 mL), washed by brine (3 x 10 mL), dried over anhydrous $MgSO_4$, concentrated *in vacuo*, and chromatographed (pentane/diethyl ether = 50/1) to afford the (*E*)-ethyl 2-diazopent-3-enoate (**5.36a**) (392.7 mg, 51%) as an orange oil.

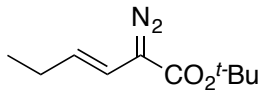
^{1}H NMR (400 MHz, $CDCl_3$): δ 5.72-5.66 (m, 1H), 5.32-5.23 (m, 1H), 4.21 (q, J = 7.6 Hz, 2H), 1.80-1.78 (m, 3H), 1.24 (t, J = 7.6 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 165.6, 120.1, 112.7, 60.9, 18.2, 14.4; IR (neat): 2981, 2073, 1698, 1252, 1122; HRMS (APCI) calcd for $C_7H_{11}O_2N_2$ $(M+H)^+$ 155.08150 found 155.08128.

[18] Lian, Y.; Davies, H. M. L. *Org. Lett*. **2010,** *12*, 924.

(*E*)-isopropyl 2-diazopent-3-enoate (**5.36b**)

Prepared according to the general procedure for the synthesis of vinyl diazoacetates. To a stirred solution of crude (*E*)-isopropyl pent-3-enoate (ca. 710 mg, ca. 5.0 mmol, 1.0 equiv) and *p*-acetamidobenzenesulfonyl azide (*p*-ABSA) (6.0 g, 25 mmol, 5.0 equiv) in acetonitrile, DBU (6.0 mL, 40 mmol, 8.0 equiv) was added drop-wise at 0 °C. The reaction mixture was then stirred overnight. Then, saturated aqueous ammonium chloride (10 mL) was added. The crude mixture was extracted with pentane (3 x 50 mL), washed by brine (3 x 10 mL), dried over anhydrous $MgSO_4$, concentrated *in vacuo*, and chromatographed (pentane/diethyl ether = 50/1) to afford the (*E*)-isopropyl 2-diazopent-3-enoate (**5.36b**) (487.2 mg, 58%) as an orange oil.

^{1}H NMR (400 MHz, $CDCl_3$): δ 5.74-5.70 (m, 1H), 5.34-5.25 (m, 1H), 5.15-5.06 (m, 1H), 1.80-1.78 (m, 3H), 1.25 (d, J = 5.2 Hz, 6H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 165.2, 119.9, 112.9, 68.5, 21.9, 18.1; IR (neat): 2981, 2073, 1693, 1251, 1104; HRMS (APCI) calcd for $C_8H_{13}O_2N_2$ $(M+H)^+$ 169.09715 found 169.09687.

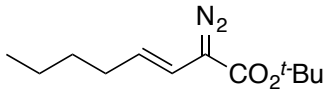


(*E*)-*tert*-butyl 2-diazohex-3-enoate (**5.36c**)

Prepared according to the general procedure for the synthesis of vinyl diazoacetates. To a stirred solution of crude (*E*)-*tert*-butyl hex-3-enoate (850 mg, 5.0 mmol, 1.0 equiv) and *p*-acetamidobenzenesulfonyl azide (*p*-ABSA) (6.0 g, 25 mmol, 5.0 equiv) in acetonitrile, DBU (6.0 mL, 40 mmol, 8.0 equiv) was added dropwise at 0 °C. The reaction mixture was then stirred overnight. Then, saturated aqueous ammonium chloride (20 mL) was added. The crude mixture was extracted with pentane (3 x 50 mL), washed by brine (3 x

10 mL), dried over anhydrous $MgSO_4$, concentrated *in vacuo*, and chromatographed (pentane/diethyl ether = 50/1) to afford the (*E*)-*tert*-butyl 2-diazohex-3-enoate (**5.36c**) (508 mg, 52%) as an orange oil.

^{1}H NMR (400 MHz, $CDCl_3$): δ 5.72-5.67 (m, 1H), 5.64 (d, *J* = 16.0 Hz, 1H), 5.31-5.25 (m, 1H), 2.15-2.12 (m, 3H), 1.45 (s, 9H), 0.96 (t, *J* = 8.0 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 164.9, 126.6, 111.3, 81.6, 28.3, 25.8, 13.8; IR (neat): 2970, 2077, 1698, 1338, 1135; HRMS (APCI) calcd for $C_{10}H_{17}O_2N_2$ $(M+H)^+$ 197.12845 found 197.12825.

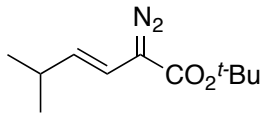


(*E*)-t*ert*-butyl 2-diazooct-3-enoate (**5.36d**)

Prepared according to the general procedure for the synthesis of vinyl diazoacetates. To a stirred solution of crude (*E*)-*tert*-butyl oct-3-enoate (990 mg, 5.0 mmol, 1.0 equiv) and *p*-acetamidobenzenesulfonyl azide (*p*-ABSA) (6.0 g, 25 mmol, 5.0 equiv) in acetonitrile, DBU (6.0 mL, 40 mmol, 8.0 equiv) was added drop-wise at 0 °C. The reaction mixture was then stirred overnight. Then, saturated aqueous ammonium chloride was added. The crude mixture was extracted with pentane (3 x 50 mL), washed by brine (3 x 10 mL), dried over anhydrous $MgSO_4$, concentrated *in vacuo*, and chromatographed (pentane/diethyl ether = 50/1) to afford the (*E*)-*tert*-butyl 2-diazooct-3-enoate (**5.36e**) (236.7 mg, 21%) as an orange oil.

^{1}H NMR (400 MHz, $CDCl_3$): δ 5.69 (d, *J* = 15.6 Hz, 1H), 5.31-5.24 (m, 1H), 2.16 (q, *J* = 6.6 Hz, 2H), 1.51 (s, 9H), 1.38-1.32 (m, 4H), 0.90 (t, *J* = 7.2 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 164.9, 125.2, 112.0, 81.7, 32.5, 31.7, 28.3, 22.1, 13.9; IR (neat): 2959,

2929, 2073, 1698, 1133 1698, 1307; HRMS (APCI) calcd for $C_{12}H_{21}O_2N_2$ $(M+H)^+$ 225.15975 found 225.15958



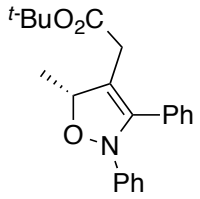
(*E*)-*tert*-butyl 2-diazo-5-methylhex-3-enoate (**5.36f**)

Prepared according to general procedure for the synthesis of vinyl diazoacetates. To a stirred solution of crude (*E*)-*tert*-butyl 2-diazo-5-methylhex-3-enoate (921 mg, 5.0 mmol, 1.0 equiv) and *p*-acetamidobenzenesulfonyl azide (*p*-ABSA) (6.0 g, 25 mmol, 5.0 equiv) in acetonitrile (30 mL), DBU (6.0 mL, 40 mmol, 8.0 equiv) was added drop-wise at 0 °C. The reaction mixture was then stirred overnight. Then, saturated aqueous ammonium chloride (20 mL) was added. The crude mixture was extracted with pentane (3 x 50 mL), washed by brine (3 x 10 mL), dried over anhydrous $MgSO_4$, concentrated *in vacuo*, and chromatographed (pentane/diethyl ether = 50/1) to afford the (*E*)-isopropyl 2-diazopent-3-enoate (**5.36f**) (380 mg, 36%) as an orange oil.

^{1}H NMR (400 MHz, $CDCl_3$): δ 5.67 (d, J = 16.0 Hz, 1H), 5.25 (dd J = 6.4, 16.0 Hz, 1H), 2.46-2.41 (m, 1H), 1.45 (s, 9H), 1.03 (d, J = 6.4 Hz, 6H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 164.9, 131.9, 109.6, 81.6, 31.4, 28.3, 22.5; IR (neat): 2963, 2074, 1698, 1307; HRMS (APCI) calcd for $C_{11}H_{19}O_2N_2$ $(M+H)^+$ 211.14410 found 211.14390.

General procedure for enantioselective [3+2]-annulation

To a 25 mL flame-dried round-bottom flask, kept under a dry atmosphere of argon, was added dry pentane (4.0 mL) and Rh_2(*R*-TPCP)$_4$ (11.2 mg, 2.0 mol%) and nitrone (0.4 mmol, 1.0 equiv). The diazo compound (0.8 mmol, 2.0 equiv), dissolved in dry pentane (4.0 mL), was then added to the former solution drop-wise over 2.0 hours at room temperature. The mixture was allowed to stir for overnight after the addition. The reaction mixture was concentrated *in vacuo* and the crude residue was analyzed by ^{1}H NMR with freshly opened $CDCl_3$ kept under potassium carbonate as solvent and purified by flash column chromatography (hexanes/ethyl acetate) to afford the pure 2,5-dihydroisoxazole derivatives.

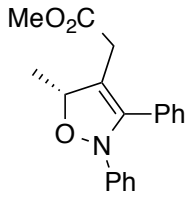


tert-butyl (*R*)-2-(5-methyl-2,3-diphenyl-2,5-dihydroisoxazol-4-yl)acetate (***R*-5.37**)

Prepared according to the general procedure for enantioselective [3+2]-annulation using (*Z*)-*N*-benzylideneaniline oxide (**5.30**) (0.4 mmol, 78.8 mg, 1.0 equiv) and Rh_2(*R*-TPCP)$_4$ (11.6 mg, 2.0 mol%) and (*E*)-*tert*-butyl 2-diazopent-3-enoate (**5.36**) (0.8 mmol, 145.6 mg, 2.0 equiv) in pentane at room temperature. The crude residue was analyzed by ^{1}H NMR and purified by flash column chromatography (hexanes/ethyl acetate = 50/1) to afford the product (***R*-5.37**) as a yellow oil (108.1 mg, 77%).

$[\alpha]^{20}_D$ -27.4° (*c* = 1.63, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.52 (d, *J* = 8.0 Hz, 2H), 7.33-7.19 (m, 7H), 7.12-7.08 (m, 1H), 5.42 (q, *J* = 6.2 Hz, 1H), 3.23 (d, *J* = 15.4 Hz, 1H), 3.12 (d, *J* = 15.4 Hz, 1H), 1.51 (s, 9H), 1.46 (d, *J* = 6.2 Hz, 1H); ^{13}C NMR (100 MHz,

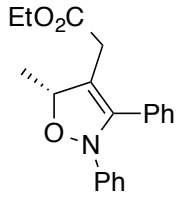
$CDCl_3$) δ 169.9, 148.2, 142.6, 130.6, 128.7, 128.6, 126.4, 124.1, 115.5, 82.9, 81.5, 32.8, 28.1, 20.0; IR (neat): 2976, 2928, 1726, 1596, 1488, 1145; HRMS (APCI) calcd for $C_{22}H_{26}O_3N$ $(M+H)^+$ 352.19072 found 352.19135; HPLC (ADH, 0% isopropanol in hexane, 0.5 mL/min, 1 mg/mL, 30 min, UV 254 nm) retention times of 20.3 min (minor) and 23.2 min (major), 98% ee.



(*R*)-methyl 2-(5-methyl-2,3-diphenyl-2,5-dihydroisoxazol-4-yl)acetate (**5.38a**)

Prepared according to the general procedure for enantioselective [3+2]-annulation using (*E*)-methyl 2-diazopent-3-enoate (**5.23**) (0.8 mmol, 112.0 mg, 2.0 equiv) and (*Z*)-*N*-benzylideneaniline oxide (**5.30**) (78.8 mg, 1.0 equiv). The crude residue was analyzed by ^{1}H NMR and purified by flash column chromatography (hexanes/ethyl acetate = 50/1) to afford the product (**5.38a**) as a yellow oil (65.3 mg, 47%).

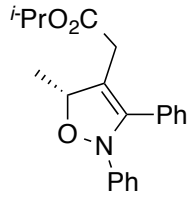
$[\alpha]^{20}_D$ -56.1° (*c* = 2.20, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.49-7.47 (m, 2H), 7.34-7.19 (m, 7H), 7.12-7.08 (m, 1H), 5.44 (q, *J* = 6.2 Hz, 1H), 3.77 (s, 3H), 3.34 (d, *J* = 16.0 Hz, 1H), 3.20 (d, *J* = 16.0 Hz, 1H), 1.47 (d, *J* = 6.2 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 171.2, 148.1, 143.3, 130.5, 128.8, 128.7, 128.6, 128.0, 126.3, 123.9, 114.5, 82.7, 52.2, 31.1, 20.1; IR (neat): 2952, 1735, 1592, 1201; HRMS (APCI) calcd for $C_{19}H_{20}O_3N$ $(M+H)^+$ 310.14377 found 310.14404; HPLC (ODR, 0.5% isopropanol in hexane, 1.0 mL/min, 1 mg/mL, 30 min, UV 254 nm) retention times of 7.3 min (minor) and 8.1 min (major), 96% ee.



(*R*)-ethyl 2-(5-methyl-2,3-diphenyl-2,5-dihydroisoxazol-4-yl)acetate (**5.38b**)

Prepared according to the general procedure for enantioselective [3+2]-annulation using (*E*)-ethyl 2-diazopent-3-enoate (**5.36b**) (0.8 mmol, 123.2 mg, 2.0 equiv) and (*Z*)-*N*-benzylideneaniline oxide (**5.30**) (78.8 mg, 1.0 equiv). The crude residue was analyzed by ^{1}H NMR and purified by flash column chromatography (hexanes/ethyl acetate = 50/1) to afford the product (**5.38b**) as a yellow oil (81.5 mg, 58%).

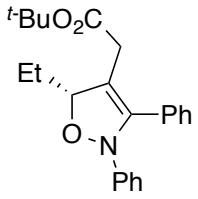
$[\alpha]^{20}_{D}$ -12.9° (*c* = 0.8, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.51-7.49 (m, 2H), 7.35-7.20 (m, 7H), 7.13-7.10 (m, 1H), 5.45 (q, *J* = 6.0 Hz, 1H), 4.21 (q, *J* = 7.0 Hz, 2H), 3.32 (d, *J* = 16.2 Hz, 1H), 3.20 (d, *J* = 16.2 Hz, 1H), 1.47 (d, *J* = 6.0 Hz, 1H), 1.33 (t, *J* = 7.0 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 170.8, 148.0, 143.0, 130.4, 128.7, 128.6, 127.9, 126.4, 124.0, 120.8, 114.9, 82.8, 77.3, 77.0, 76.7, 61.2, 31.3, 20.1, 14.2; IR (neat): 2952, 1736, 1595, 1202; HRMS (APCI) calcd for $C_{20}H_{22}O_3N$ $(M+H)^+$ 324.15942 found 324.15927; HPLC (ODR, 0.5% isopropanol in hexane, 1.0 mL/min, 1 mg/mL, 30 min, UV 254 nm) retention times of 6.5 min (minor) and 7.2 min (major), 98% ee.



(*R*)-isopropyl 2-(5-methyl-2,3-diphenyl-2,5-dihydroisoxazol-4-yl)acetate (**5.38c**)

Prepared according to the general procedure for enantioselective [3+2]-annulation using (*E*)-*isopropyl* 2-diazopent-3-enoate (**5.36c**) (0.8 mmol, 134.4 mg, 2.0 equiv) and (*Z*)-*N*-benzylideneaniline oxide (**5.30**) (78.8 mg, 1.0 equiv). The crude residue was analyzed by ^{1}H NMR and purified by flash column chromatography (hexanes/ethyl acetate = 50/1) to afford the product (**5.38c**) as a yellow oil (94.2 mg, 67%).

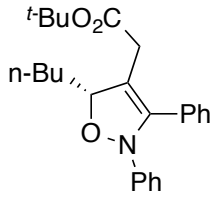
$[\alpha]^{20}_{D}$ -83.7° (*c* = 1.1, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.53-7.50 (m, 2H), 7.34-7.19 (m, 7H), 7.12-7.08 (m, 1H), 5.42 (q, *J* = 6.2 Hz, 1H), 5.13-5.07 (m, 1H), 3.29 (d, *J* = 16.0 Hz, 1H), 3.17 (d, *J* = 16.0 Hz, 1H), 1.46 (d, *J* = 6.2 Hz, 3H), 1.29 (d, *J* = 6.0 Hz, 6H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 170.3, 148.1, 142.9, 130.5, 128.8, 128.7, 128.6, 126.5, 124.1, 115.0, 82.9, 68.7, 31.6, 21.8, 20.1; IR (neat): 2979, 1729, 1597, 1105; HRMS (APCI) calcd for $C_{21}H_{24}O_3N$ $(M+H)^+$ 338.17507 found 338.17493; HPLC (S,S-Whelk, 0% isopropanol in hexane, 0.25 mL/min, 1 mg/mL, 80 min, UV 254 nm) retention times of 50.9 min (minor) and 56.5 min (major), 99% ee.



(*R*)-*tert*-butyl 2-(5-ethyl-2,3-diphenyl-2,5-dihydroisoxazol-4-yl)acetate (**5.38d**)

Prepared according to the general procedure for enantioselective [3+2]-annulation using (*E*)-*tert*-butyl 2-diazohex-3-enoate (**5.36d**) (0.8 mmol, 156.9 mg, 2.0 equiv) and (*Z*)-*N*-benzylideneaniline oxide (**5.30**) (78.8 mg, 1.0 equiv). The crude residue was analyzed by ^{1}H NMR and purified by flash column chromatography (hexanes/ethyl acetate = 50/1) to afford the product (**5.38d**) as an oil (105.5 mg, 72%).

$[\alpha]^{20}_{D}$ -27.3° (*c* = 4.0, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.53-7.48 (m, 2H), 7.33-7.17 (m, 7H), 7.10-7.06 (m, 1H), 5.32-5.30 (m, 1H), 3.23 (d, *J* = 15.6 Hz, 1H), 3.08 (d, *J* = 15.6 Hz, 1H), 1.93-1.84 (m, 1H), 1.76-1.65 (m, 1H), 1.52 (s, 9H), 1.01 (t, *J* = 4.0 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 169.9, 148.2, 143.1, 130.6, 128.6, 128.5, 126.2, 124.0, 114.0, 87.8, 81.4, 32.9, 28.1, 26.8, 9.3; IR (neat): 2976, 1727, 1597, 1149; HRMS (APCI) calcd for $C_{23}H_{28}O_3N$ $(M+H)^+$ 366.20637 found 366.20669; HPLC (ADH, 0% isopropanol in hexane, 0.5 mL/min, 1 mg/mL, 30 min, UV 254 nm) retention times of 17.3 min (minor) and 22.3 min (major), 94% ee.

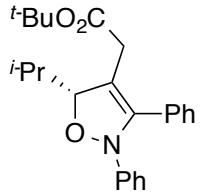


(*R*)-*tert*-butyl 2-(5-butyl-2,3-diphenyl-2,5-dihydroisoxazol-4-yl)acetate (**5.38e**)

Prepared according to the general procedure for enantioselective [3+2]-annulation using (*E*)-*tert*-butyl 2-diazooct-3-enoate (**5.36e**) (0.8 mmol, 179.2 mg, 2.0 equiv) and (*Z*)-*N*-benzylideneaniline oxide (**5.30**) (0.4 mmol, 78.8 mg, 1.0 equiv). The crude residue was analyzed by ^{1}H NMR and purified by flash column chromatography (hexanes/ethyl acetate = 50/1) to afford the product (**5.38e**) as a yellow oil (97.5 mg, 62%).

$[\alpha]^{20}_{D}$ -24.3° (*c* = 4.60, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.53-7.51 (m, 2H), 7.32-7.19 (m, 7H), 7.11-7.07 (m, 2H), 5.32 (dd, *J* = 2.8, 8.0 Hz, 1H), 3.24 (d, *J* = 15.6 Hz, 1H), 3.10 (d, *J* = 15.6 Hz, 1H), 1.85-1.80 (m, 1H), 1.70-1.67 (m, 1H), 1.52 (s, 9H), 1.37-1.30 (m, 4H), 0.89 (t, *J* = 7.6 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 169.9, 148.3, 142.9, 130.7, 128.6, 128.5, 128.2, 128.0, 126.3, 124.0, 114.5, 86.7, 81.4, 33.9, 32.9, 28.1,

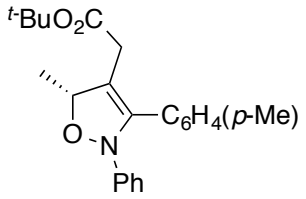
27.4, 22.7, 13.9; IR (neat): 2957, 2930, 1727, 1486, 1144; HRMS (APCI) calcd for $C_{25}H_{32}O_3N$ $(M+H)^+$ 394.23767 found 394.23790; HPLC (SSWhelk, 0% isopropanol in hexane, 0.25 mL/min, 1 mg/mL, 30 min, UV 254 nm) retention times of 23.2 min (minor) and 25.4 min (major), 94% ee.



(*R*)-*tert*-butyl 2-(5-isopropyl-2,3-diphenyl-2,5-dihydroisoxazol-4-yl)acetate (**5.38f**)

Prepared according to the general procedure for enantioselective [3+2]-annulation using (*E*)-*tert*-butyl 2-diazo-5-methylhex-3-enoate (**5.36f**) (0.8 mmol, 168.0 mg, 2.0 equiv) and (*Z*)-*N*-benzylideneaniline oxide (**5.30**) (78.8 mg, 1.0 equiv). The crude residue was analyzed by ^{1}H NMR and purified by flash column chromatography (hexanes/ethyl acetate = 50/1) to afford the product (**5.38f**) as a yellow oil (77.3 mg, 51%).

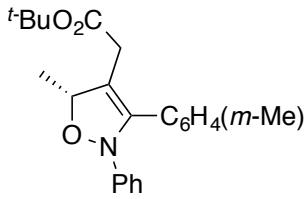
$[\alpha]^{20}_D$ -1.9° (*c* = 0.72, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.52-7.49 (m, 2H), 7.34-7.18 (m, 7H), 7.09-7.07 (m, 1H), 5.30 (d, *J* = 1.6 Hz, 1H), 3.23 (d, *J* = 15.8 Hz, 1H), 3.03 (d, *J* = 15.8 Hz, 1H), 2.05-2.01 (m, 1H), 1.51 (s, 9H), 1.06 (d, *J* = 7.0 Hz, 3H), 0.93 (d, *J* = 7.0 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 169.9, 148.2, 143.6, 130.8, 128.7, 128.6, 128.5, 126.1, 124.1, 112.9, 91.2, 81.4, 33.1, 30.5, 28.0, 19.6, 15.6; IR (neat): 2969, 1729, 1368, 1149; HRMS (APCI) calcd for $C_{24}H_{30}O_3N$ $(M+H)^+$ 380.22202 found 380.22230; HPLC (ADH, 0% isopropanol in hexane, 0.5 mL/min, 1 mg/mL, 30 min, UV 254 nm) retention times of 11.0 min (minor) and 13.2 min (major), 66% ee.



(*R*)-*tert*-butyl 2-(5-methyl-2-phenyl-3-(p-tolyl)-2,5-dihydroisoxazol-4-yl)acetate (**5.38g**)

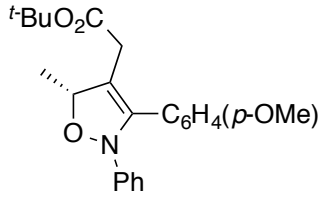
Prepared according to the general procedure for enantioselective [3+2]-annulation using (*E*)-*tert*-butyl 2-diazopent-3-enoate (**5.36**) (0.8 mmol, 145.6 mg, 2.0 equiv) and (*Z*)-*N*-(4-methylbenzylidene)aniline oxide (**5.30a**) (0.4 mmol, 84.4 mg, 1.0 equiv). The crude residue was analyzed by ^{1}H NMR and purified by flash column chromatography (hexanes/ethyl acetate = 50/1) to afford the product (**5.38g**) as a yellow oil (101.6 mg, 70%).

$[\alpha]^{20}_{D}$ -58.1° (*c* = 3.13, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.41 (d, *J* = 8.0, 2H), 7.26-7.19 (m, 4H), 7.13-7.06 (m, 3H), 5.41 (q, *J* = 6.2 Hz, 1H), 3.22 (d, *J* = 15.6 Hz, 1H), 3.11 (d, *J* = 15.6 Hz, 1H), 2.23 (s, 3H), 1.51 (s, 9H), 1.45 (d, *J* = 6.2 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 170.0, 148.2, 142.6, 138.6, 129.3, 128.7, 128.4, 127.6, 126.3, 124.1, 114.9, 82.8, 81.4, 32.8, 28.0, 21.3, 20.0; IR (neat): 2955, 2924, 1728, 1488, 1250; HRMS (APCI) calcd for $C_{23}H_{28}O_3N$ $(M+H)^+$ 366.20637 found 366.20663; HPLC (ADH, 0% isopropanol in hexane, 0.5 mL/min, 1 mg/mL, 60 min, UV 254 nm) retention times of 26.3 min (minor) and 49.3 min (major), 93% ee.



(*R*)-*tert*-butyl 2-(5-methyl-2-phenyl-3-(m-tolyl)-2,5-dihydroisoxazol-4-yl)acetate (**5.38h**)

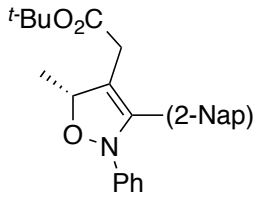
Prepared according to the general procedure for enantioselective [3+2]-annulation using (*E*)-*tert*-butyl 2-diazopent-3-enoate (**5.36**) (0.8 mmol, 145.6 mg, 2.0 equiv) and (*Z*)-*N*-(3-methylbenzylidene)aniline oxide (**5.30b**) (0.4 mmol, 84.4 mg, 1.0 equiv). The crude residue was analyzed by ^{1}H NMR and purified by flash column chromatography (hexanes/ethyl acetate = 50/1) to afford the product **(5.38h**) as an oil (92.9 mg, 64%). $[\alpha]^{20}_{D}$ -78.9° (*c* = 4.75, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.35-7.31 (m, 2H), 7.26-7.18 (m, 5H), 7.11-7.07 (m, 2H), 5.41 (q, *J* = 5.8 Hz, 1H), 3.23 (d, *J* = 15.8 Hz, 1H), 3.12 (d, *J* = 15.8 Hz, 1H), 2.29 (s, 3H), 1.51 (s, 9H), 1.45 (d, *J* = 5.8 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 169.9, 148.3, 142.7, 138.1, 130.5, 129.5, 129.1, 128.7, 128.4, 126.3, 125.6, 123.9, 115.5, 82.9, 81.4, 32.8, 28.1, 21.4, 20.0; IR (neat): 2976, 2927, 1728, 1488, 1256; HRMS (APCI) calcd for $C_{23}H_{28}O_3N$ $(M+H)^+$ 366.20637 found 366.20589; HPLC (ADH, 0% isopropanol in hexane, 0.5 mL/min, 1 mg/mL, 60 min, UV 254 nm) retention times of 19.3 min (minor) and 22.9 min (major), 97% ee.



(*R*)-*tert*-butyl 2-(3-(4-methoxyphenyl)-5-methyl-2-phenyl-2,5-dihydroisoxazol-4-yl)acetate (**5.38i**)

Prepared according to the general procedure for enantioselective [3+2]-annulation using (*E*)-*tert*-butyl 2-diazopent-3-enoate (**5.36**) (0.8 mmol, 145.6 mg, 2.0 equiv) and (*Z*)-*N*-(4-methoxybenzylidene)aniline oxide (**5.30c**) (0.4 mmol, 90.8 mg, 1.0 equiv). The crude

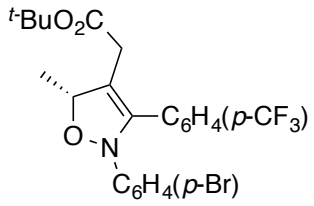
residue was analyzed by ^{1}H NMR and purified by flash column chromatography (hexanes/ethyl acetate = 50/1) to afford the product (**5.38i**) as an oil (91.5 mg, 60%). $[\alpha]^{20}_D$ -69.9° (*c* = 3.15, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.44 (d, *J* = 8.8 Hz, 2H), 7.24-7.17 (m, 4H), 7.10-7.06 (m, 1H), 6.82 (d, *J* = 8.8 Hz, 2H), 5.38 (q, *J* = 6.2 Hz, 1H), 3.75 (s, 3H), 3.19 (d, *J* = 15.6 Hz, 1H), 3.09 (d, *J* = 15.6 Hz, 1H), 1.49 (s, 9H), 1.42 (d, *J* = 6.2 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 170.1, 159.7, 148.3, 142.3, 129.9, 128.7, 126.3, 124.1, 122.9, 114.4, 113.9, 82.8, 81.4, 55.2, 32.8, 28.1, 19.9; IR (neat): 2976, 2934, 1727, 1512, 1147; HRMS (APCI) calcd for $C_{23}H_{28}O_4N$ $(M+H)^+$ 382.20129 found 382.20105; HPLC (ODR, 0% isopropanol in hexane, 0.5 mL/min, 1 mg/mL, 30 min, UV 254 nm) retention times of 9.5 min (minor) and 11.4 min (major), 95% ee.



(*R*)-*tert*-butyl 2-(34methyl-3-(naphthalen-2-yl)-2-phenyl-2,5-dihydroisoxazol-4-yl)acetate (**5.38j**)

Prepared according to the general procedure for enantioselective [3+2]-annulation using (*E*)-*tert*-butyl 2-diazopent-3-enoate (**5.36**) (0.8 mmol, 145.6 mg, 2.0 equiv) and (*Z*)-*N*-(naphthalen-2-ylmethylene)aniline (**5.30d**) (0.4 mmol, 98.8 mg, 1.0 equiv). The crude residue was analyzed by ^{1}H NMR and purified by flash column chromatography (hexanes/ethyl acetate = 50/1) to afford the product (**5.38j**) as an oil (110.6 mg, 69%). $[\alpha]^{20}_D$ -6.12° (*c* = 2.30, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.04-8.03 (m, 1H), 7.80-7.76 (m, 3H), 7.65-7.63 (m, 1H), 7.48-7.44 (m, 2H), 7.30-7.27 (m, 2H), 7.20-7.15 (m,

2H), 7.07-7.03 (m, 1H), 5.47 (q, J = 6.2 Hz, 1H), 3.29 (d, J = 16.0 Hz, 1H), 3.19 (d, J = 16.0 Hz, 1H), 1.54 (s, 9H), 1.50 (d, J = 6.2 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ169.9, 148.2, 142.7, 133.2, 133.1, 128.7, 128.3, 128.2, 128.1, 127.9, 127.6, 126.6, 126.3, 125.9, 123.9, 116.1, 83.0, 81.5, 32.9, 28.1, 20.1; IR (neat): 2976, 2929, 1726, 1147; HRMS (APCI) calcd for $C_{26}H_{27}O_3N$ $(M)^+$ 401.19855 found 401.19899; HPLC (S,S-WHELK, 0% isopropanol in hexane, 0.25 mL/min, 1 mg/mL, 100 min, UV 254 nm) retention times of 61.9 min (major) and 73.4 min (minor), 96% ee.

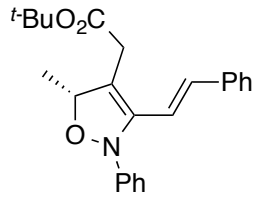


(*R*)-*tert*-butyl 2-(2-(4-bromophenyl)-5-methyl-3-(4-(trifluoromethyl)phenyl)-2,5-dihydroisoxazol-4-yl)acetate (**5.38k**)

Prepared according to the general procedure for enantioselective [3+2]-annulation using (*E*)-*tert*-butyl 2-diazopent-3-enoate (**5.36**) (0.8 mmol, 145.6 mg, 2.0 equiv) and (*Z*)-4-bromo-*N*-(4-(trifluoromethyl)benzylidene)aniline oxide (**5.30e**) (0.4 mmol, 136.8 mg, 1.0 equiv). The crude residue was analyzed by ^{1}H NMR and purified by flash column chromatography (hexanes/ethyl acetate = 100/1) to afford the product (**5.38k**) as an oil (83.3 mg, 42%).

$[\alpha]^{20}_D$ -5.5° (*c* = 1.10, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.63 (q, J = 8.6 Hz, 4H), 7.35 (d, J = 9.0 Hz, 2H), 7.10 (d, J = 9.0 Hz, 2H), 5.38 (q, J = 6.2 Hz, 1H), 3.21-3.11 (m, 1H), 1.52 (s, 9H), 1.46 (d, J = 6.2 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 169.4, 146.9, 141.2, 133.9, 132.2, 132.0, 130.7, 129.8, 128.8, 125.8, 125.7, 125.6, 122.4, 120.1, 117.9;

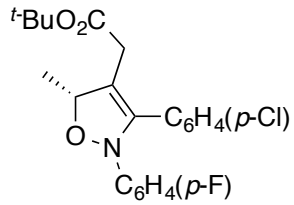
IR (neat): 2924, 2854, 1727, 1325, 1166; HRMS (APCI) calcd for $C_{23}H_{24}O_3NBrF_3$ $(M+H)^+$ 498.08862 found 498.08951; HPLC (ADH, 0% isopropanol in hexane, 0.25 mL/min, 1 mg/mL, 60 min, UV 254 nm) retention times of 31.2 min (minor) and 36.0 min (major), 85% ee.



(*R*,*E*)-*tert*-butyl 2-(5-methyl-2-phenyl-3-styryl-2,5-dihydroisoxazol-4-yl)acetate (**5.38l**)

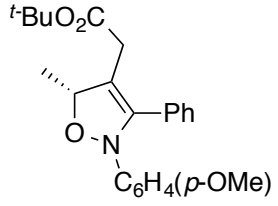
Prepared according to the general procedure for enantioselective [3+2]-annulation using (*E*)-*tert*-butyl 2-diazopent-3-enoate (**5.36**) (0.8 mmol, 145.6 mg, 2.0 equiv) and (*Z*)-*N*-((*E*)-3-phenylallylidene)aniline oxide (**5.30f**) (0.4 mmol, 90.8 mg, 1.0 equiv). The crude residue was analyzed by ^{1}H NMR and purified by flash column chromatography (hexanes/ethyl acetate = 50/1) to afford the product (**5.38l**) as an oil (93.5 mg, 62%).

$[\alpha]^{20}_D$ -31.8° (*c* = 1.24, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.37-7.07 (m, 10H), 6.74 (d, *J* = 16.0 Hz, 1H), 6.51 (d, *J* = 16.0 Hz, 1H), 5.38 (q, *J* = 6.0 Hz, 1H), 3.36 (d, *J* = 15.6 Hz, 1H), 3.20 (d, *J* = 15.6 Hz, 1H), 1.47 (s, 9H), 1.36 (d, *J* = 6.2 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 169.0, 148.5, 140.2, 136.5, 134.3, 128.8, 128.6, 128.2, 126.7, 126.6, 124.0, 121.0, 115.0, 81.7, 81.5, 32.4, 28.0, 19.2; IR (neat): 2975, 2925, 1726, 1368, 1150; HRMS (APCI) calcd for $C_{24}H_{28}O_3N$ $(M+H)^+$ 378.20637 found 378.20671; HPLC (ODR, 0.5% isopropanol in hexane, 1.0 mL/min, 1 mg/mL, 30 min, UV 254 nm) retention times of 6.5 min (minor) and 7.5 min (major), 42% ee.



(*R*)-*tert*-butyl 2-(3-(4-chlorophenyl)-2-(4-fluorophenyl)-5-methyl-2,5-dihydroisoxazol-4-yl)acetate (**5.38m**)

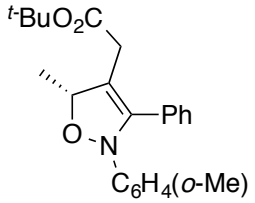
Prepared according to the general procedure for enantioselective [3+2]-annulation using (*E*)-*tert*-butyl 2-diazopent-3-enoate (**5.36**) (0.8 mmol, 145.6 mg, 2.0 equiv) and (*Z*)-*N*-(4-chlorobenzylidene)-4-fluoroaniline oxide (**5.30g**) (0.4 mmol, 99.6 mg, 1.0 equiv). The crude residue was analyzed by ^{1}H NMR and purified by flash column chromatography (hexanes/ethyl acetate = 50/1) to afford the product (**5.38m**) as an oil (94.4 mg, 59%). $[\alpha]^{20}_{D}$ -18.5° (*c* = 1.30, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.44 (d, *J* = 8.8 Hz, 2H), 7.24-7.17 (m, 4H), 7.10-7.06 (m, 1H), 6.82 (d, *J* = 8.8 Hz, 2H), 5.38 (q, *J* = 6.2 Hz, 1H), 3.75 (s, 3H), 3.19 (d, *J* = 15.6 Hz, 1H), 3.09 (d, *J* = 15.6 Hz, 1H), 1.49 (s, 9H), 1.42 (d, *J* = 6.2 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 169.8, 161.4 ($^{1}J_{C\text{-}F}$ = 245.5 Hz), 143.7, 141.9, 134.7, 129.8, 128.9, 128.7, 126.8, 126.7, 116.0, 115.8, 115.6, 83.0, 81.8, 32.7, 28.0, 20.1; IR (neat): 2971, 2930, 1727, 1500, 1368; HRMS (APCI) calcd for $C_{22}H_{24}O_3NClF$ $(M+H)^+$ 404.14233 found 404.14283; HPLC (ADH, 0% isopropanol in hexane, 0.25 mL/min, 1 mg/mL, 30 min, UV 254 nm) retention times of 37.5 min (minor) and 57.7 min (major), 95% ee.



(*R*)-*tert*-butyl 2-(2-(4-methoxyphenyl)-5-methyl-3-phenyl-2,5-dihydroisoxazol-4-yl)acetate (**5.38n**)

Prepared according to the general procedure for enantioselective [3+2]-annulation using using (*E*)-*tert*-butyl 2-diazopent-3-enoate (**5.36**) (0.8 mmol, 145.6 mg, 2.0 equiv) and (*Z*)-*N*-benzylidene-4-methoxyaniline oxide (**5.30h**) (0.4 mmol, 90.8 mg, 1.0 equiv). The crude residue was analyzed by ^{1}H NMR and purified by flash column chromatography (hexanes/ethyl acetate = 50/1) to afford the product (**5.38n**) as a yellow oil (100.6 mg, 66%).

$[\alpha]^{20}_D$ -16.0° (*c* = 1.60, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.44 (d, *J* = 8.8 Hz, 2H), 7.24-7.17 (m, 5H), 6.76-6.74 (m, 2H), 5.41 (q, *J* = 5.6 Hz, 1H), 3.72 (s, 3H), 3.22 (d, *J* = 15.6 Hz, 1H), 3.12 (d, *J* = 15.6 Hz, 1H), 1.53 (s, 9H), 1.46 (d, *J* = 6.2 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 170.1, 158.6, 143.1, 140.6, 130.4, 128.6, 128.5, 126.9, 114.7, 113.9, 82.6, 81.4, 55.3, 32.8, 28.1, 20.2; IR (neat): 2975, 2929, 1727, 1504, 1248, 1147; HRMS (APCI) calcd for $C_{23}H_{28}O_4N$ $(M+H)^+$ 382.20129 found 382.20154; HPLC (ODR, 0% isopropanol in hexane, 0.5 mL/min, 1 mg/mL, 55 min, UV 254 nm) retention times of 11.3 min (minor) and 12.1 min (major), 90% ee.



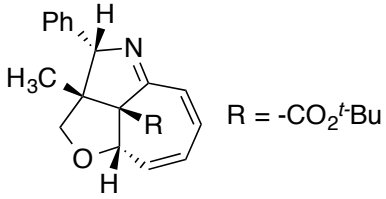
(*R*)-*tert*-butyl 2-(5-methyl-3-phenyl-2-(o-tolyl)-2,5-dihydroisoxazol-4-yl)acetate (**5.38o**)

Prepared according to the general procedure for enantioselective [3+2]-annulation using (*E*)-*tert*-butyl 2-diazopent-3-enoate (**3.36**) (0.8 mmol, 145.6 mg, 2.0 equiv) and (*Z*)-N-

benzylidene-2-methylaniline oxide (**5.30i**) (0.4 mmol, 84.4 mg, 1.0 equiv). The crude residue was analyzed by ^{1}H NMR and purified by flash column chromatography (hexanes/ethyl acetate = 50/1) to afford the product (**5.38o**) as a colorless oil (65.7 mg, 45%).

$[\alpha]^{20}_D$ -32.3° (*c* = 1.00, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.52-7.50 (m, 2H), 7.30-7.22 (m, 4H), 7.16-7.14 (m, 1H) 7.06-7.01 (m, 2H), 5.35 (q, *J* = 5.6 Hz, 1H), 3.26 (d, *J* = 15.6 Hz, 1H), 3.17 (d, *J* = 15.6 Hz, 1H), 2.52 (s, 3H), 1.52 (s, 9H), 1.44 (d, *J* = 5.6 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 170.2, 145.3, 142.5, 136.9, 130.8, 130.6, 128.6, 128.5, 128.3, 127.5, 126.1, 124.2, 115.4, 82.6, 81.5, 32.9, 28.1, 27.9, 20.1, 17.9; IR (neat): 2976, 2926, 1726, 1149; HRMS (APCI) calcd for $C_{23}H_{28}O_3N$ $(M+H)^+$ 366.20637 found 366.20673; HPLC (ADH, 0% isopropanol in hexane, 0.15 mL/min, 1 mg/mL, 45 min, UV 254 nm) retention times of 34.6 min (minor) and 36.5 min (major), 87% ee.

Representative procedure for Rh_2(*R*-DPCP)$_4$-catalyzed cascade towards tricyclic compound synthesis



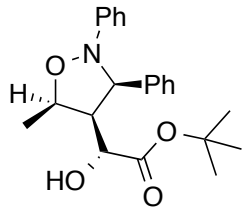
Tert-butyl (2a*S*,2a1*S*,3*S*,8a*S*)-2a-methyl-3-phenyl-2,2a,3,8a-tetrahydro-2a1H-1-oxa-4-azacyclopenta[cd]azulene-2a1-carboxylate (**5.48**)

To a 25 mL round-bottom flask, kept under a dry atmosphere of argon, was added undry pentane (4.0 mL) and Rh_2(*R*-DPCP)$_4$ (11.2 mg, 0.02 equiv) and (*Z*)-*N*-benzylideneaniline oxide (**5.30**) (78.8 mg, 1.0 equiv), (*E*)-*tert*-butyl 2-diazopent-3-enoate (**5.36**) (0.8 mmol, 145.6 mg, 2.0 equiv), dissolved in dry pentane (4.0 mL), was then added to the former

solution drop-wise over 2.0 hours at room temperature. The mixture was allowed to stir for overnight after the addition. The reaction mixture was concentrated *in vacuo* and the crude residue was analyzed by ^{1}H NMR with freshly opened $CDCl_3$ kept under potassium carbonate as solvent and purified by flash column chromatography (hexanes/ethyl acetate = 50/1) to afford the product (**5.48**) as a colorless oil (58.9 mg, 42%).

^{1}H NMR (400 MHz, $CDCl_3$): δ 7.48 (d, J = 7.2 Hz, 2H), 7.31 (t, J = 7.6 Hz, 2H), 7.27-7.22 (m, 1H), 6.77 (d, J = 11.6 Hz, 1H), 6.41-6.37 (m, 1H), 6.23-6.21 (m, 1H), 5.56 (d, J = 6.4 Hz, 1H), 4.63-4.62 (m, 1H), 4.17-4.11 (m, 1H), 3.67-3.63 (m, 1H), 1.42 (s, 9H), 0.52 (d, J = 6.4 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 169.4, 168.9, 140.2, 130.7, 129.9, 128.7, 128.3, 126.9, 126.7, 82.6, 78.8, 74.2, 74.1, 57.4, 27.8, 19.4; IR (neat): 2977, 1721, 1369, 1155; HRMS (APCI) calcd for $C_{22}H_{26}O_3N$ $(M+H)^+$ 352.19072 found 352.19090; HPLC (ADH, 0% isopropanol in hexane, 0.5 mL/min, 1 mg/mL, 60 min, UV 254 nm) retention times of 43.7 min (minor) and 46.4 min (major), 84% ee.

Representative procedure for Rh_2(*R*-DPCP)$_4$-catalyzed cascade O-H insertion reaction



tert-butyl (*R*)-2-hydroxy-2-((3*R*,4*S*,5*R*)-5-methyl-2,3-diphenylisoxazolidin-4-yl)acetate (**5.49**)

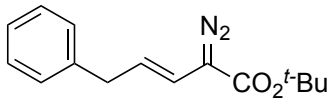
To a 25 mL flame-dried round-bottom flask, kept under a dry atmosphere of argon, was added undry pentane (4.0 mL) and Rh_2(*R*-DPCP)$_4$ (11.2 mg, 0.02 equiv) and (*Z*)-*N*-

benzylideneaniline oxide (**5.30**) (78.8 mg, 1.0 equiv), (*E*)-*tert*-butyl 2-diazopent-3-enoate (**5.36**) (0.8 mmol, 145.6 mg, 2.0 equiv), dissolved in undry pentane (4.0 mL), was then added to the former solution drop-wise over 2.0 hours at -45 ^{o}C. The mixture was allowed to stir for overnight after the addition. The reaction mixture was concentrated *in vacuo* and the crude residue was analyzed by ^{1}H NMR with freshly opened $CDCl_3$ kept under potassium carbonate as solvent and purified by flash column chromatography (hexanes/ethyl acetate = 50/1) to afford the product (**5.49)** (56.9 mg, 39%).

^{1}H NMR (400 MHz, $CDCl_3$): δ 7.50-7.48 (m, 2H), 7.36-7.32 (t, *J* = 7.2 Hz, 2H), 7.25-7.19 (m, 3H), 6.97-6.95 (m, 2H), 6.90-6.84 (m, 1H), 4.74 (d, *J* = 7.2 Hz, 1H), 4.28-4.24 (m, 1H), 4.07-4.05 (m, 1H), 3.06 (d, *J* = 4.8 Hz, 1H), 2.71-2.66 (m, 1H), 1.50 (d, *J* = 6.0 Hz, 3H), 1.16 (s, 9H); ^{13}C NMR (100 MHz, $CDCl_3$) δ172.6, 152.3, 142.5, 128.8, 127.5, 127.4, 126.9, 121.3, 121.1, 114.3, 113.8, 83.9, 83.7, 76.2, 71.0, 67.7, 63.9, 27.6, 16.9; IR (neat): 3489, 2977, 1721, 1597, 1487, 1155; HRMS (APCI) calcd for $C_{22}H_{28}O_4N$ $(M+H)^+$ 370.20129 found 370.20128; HPLC (S,S-Whelk, 0.5% isopropanol in hexane, 0.5 mL/min, 1 mg/mL, 30 min, UV 254 nm) retention times of 16.8 min (minor) and 20.5 min (major), 71% ee.

Experimental Data for Chapter VI:

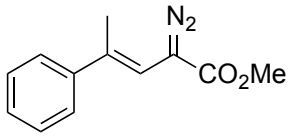
Procedure of new vinyldiazo compounds synthesis



(*E*)-*tert*-butyl 2-diazo-5-phenylpent-3-enoate (**6.4r**)

To a stirred solution of (*E*)-*tert*-butyl 5-phenylpent-3-enoate (1.2 g, 5.0 mmol, 1.0 equiv) and *p*-acetamidobenzenesulfonyl azide (*p*-ABSA) (6.1 g, 25.0 mmol, 5.0 equiv) in acetonitrile (30 mL) under argon atmosphere, DBU (6.0 mL, 40.0 mmol, 8.0 equiv) was added drop-wise at 0 °C. The reaction mixture was then stirred overnight. Then, saturated aqueous ammonium chloride (10 mL) was added. The crude mixture was extracted with pentane (3 x 50 mL), washed by brine (3 x 10 mL), dried over anhydrous $MgSO_4$, concentrated *in vacuo*, and purified by flash chromatography (pentane/diethyl ether = 50/1) to afford the (*E*)-*tert*-butyl 2-diazo-5-phenylpent-3-enoate (**6.4r**) (800 mg, 62%) as an orange oil.

^{1}H NMR (400 MHz, $CDCl_3$): δ 7.31-7.18 (m, 5H), 5.81 (d, *J* = 15.6 Hz, 1H), 5.45-5.38 (m, 1H), 3.48 (d, *J* = 7.2 Hz, 2H), 1.49 (s, 9H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 164.7, 140.1, 128.5, 126.2, 125.4, 123.2, 113.8, 81.8, 39.2, 28.3; IR (neat): 2978, 2078, 1698, 1369, 1161, 1118; HRMS (FTMS+p-NSI) calcd for $C_{15}H_{19}O_2N_2$ $(M+H)^+$ 259.14410 found 259.14390.

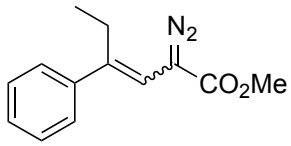


(*E*)-methyl 2-diazo-4-phenylpent-3-enoate (**6.6a**)

To a stirred solution of (*E*)-methyl 4-phenylpent-3-enoate (1.9 g, 10.0 mmol, 1.0 equiv) and *p*-acetamidobenzenesulfonyl azide (*p*-ABSA) (3.7 g, 15.0 mmol, 1.5 equiv) in acetonitrile (50 mL) under argon atmosphere, DBU (3.0 mL, 20.0 mmol, 2.0 equiv) was added drop-wise at 0 °C. The reaction mixture was then stirred overnight. Then, saturated aqueous ammonium chloride (15 mL) was added. The crude mixture was extracted with

pentane (3 x 50 mL), washed by brine (3 x 10 mL), dried over anhydrous $MgSO_4$, concentrated *in vacuo*, and purified by flash chromatography (pentane/diethyl ether = 50/1) to afford the (*E*)-methyl 2-diazo-4-phenylpent-3-enoate (**6.6a**) (1.55 g, 72%) as an orange oil.

^{1}H NMR (400 MHz, $CDCl_3$): δ 7.44-7.26 (m, 5H), 5.99 (s, 1H), 3.83 (s, 3H), 2.09 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 166.8, 142.4, 134.5, 128.2, 127.2, 125.7, 108.9, 52.2, 16.8; IR (neat): 2952, 2077, 1705, 1436, 1241, 1113; HRMS (FTMS+p-NSI) calcd for $C_{12}H_{12}O_2N_2Na$ $(M+Na)^+$ 239.07910 found 239.07896.

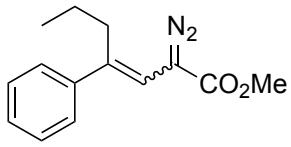


methyl 2-diazo-4-phenylhex-3-enoate (**6.6b**)

To a stirred solution of methyl 4-phenylhex-3-enoate (632 mg, 3.1 mmol, 1.0 equiv) and *p*-acetamidobenzenesulfonyl azide (*p*-ABSA) (2.3 g, 9.3 mmol, 3.0 equiv) in acetonitrile (25 mL) under argon atmosphere, DBU (2.8 mL, 18.6 mmol, 6.0 equiv) was added drop-wise at 0 °C. The reaction mixture was then stirred overnight. Then, saturated aqueous ammonium chloride (15 mL) was added. The crude mixture was extracted with pentane (3 x 50 mL), washed by brine (3 x 10 mL), dried over anhydrous $MgSO_4$, concentrated *in vacuo*, and purified by flash chromatography (pentane/diethyl ether = 50/1) to afford the methyl 2-diazo-4-phenylhex-3-enoate (**6.6b**) (*E/Z* = 8.3/1, 442 mg, 62%) as a yellow-red oil.

^{1}H NMR (400 MHz, $CDCl_3$): δ 7.39-7.24 (m, 5H), 5.85 (s, 1H), 3.82 (s, 3H), 2.55-2.50 (q, 2H), 1.00 (t, *J* = 8.0 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 167.0, 141.6, 140.9,

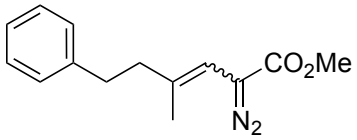
128.3, 127.3, 126.2, 108.3, 52.3, 23.6, 13.2; IR (neat): 2968, 2077, 1707, 1436, 1254, 1117; HRMS (FTMS+p-NSI) calcd for $C_{13}H_{14}O_2N_2Na$ $(M+Na)^+$ 253.09475 found 254.09473.



methyl 2-diazo-4-phenylhept-3-enoate (**6.6c**)

To a stirred solution of methyl 4-phenylhept-3-enoate (510 mg, 2.34 mmol, 1.0 equiv) and *p*-acetamidobenzenesulfonyl azide (*p*-ABSA) (1.14 g, 4.68 mmol, 2.0 equiv) in acetonitrile (15 mL) under argon atmosphere, DBU (1.4 mL, 9.4 mmol, 4.0 equiv) was added drop-wise at 0 °C. The reaction mixture was then stirred overnight. Then, saturated aqueous ammonium chloride (15 mL) was added. The crude mixture was extracted with pentane (3 x 50 mL), washed by brine (3 x 10 mL), dried over anhydrous $MgSO_4$, concentrated *in vacuo*, and purified by flash chromatography (pentane/diethyl ether = 50/1) to afford the methyl 2-diazo-4-phenylhept-3-enoate (**6.6c**) (*E/Z* = 10/1, 442 mg, 62%) as a yellow-red oil.

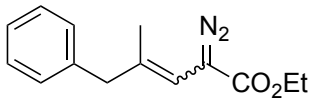
^{1}H NMR (400 MHz, $CDCl_3$): δ 7.38-7.24 (m, 5H), 5.87 (s, 1H), 3.82 (s, 3H), 2.47 (t, *J* = 8.0 Hz, 2H), 1.42-1.35 (m, 2H), 0.91 (t, *J* = 7.2 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 142.0, 139.7, 128.3, 127.2, 126.1, 108.9, 52.3, 32.4, 21.9, 13.9; IR (neat): 2957, 2873, 2075, 1706, 1436, 1359, 1243, 1118, 1096, 759, 697; HRMS (FTMS+p-NSI) calcd for $C_{14}H_{16}O_2N_2Na$ $(M+Na)^+$ 267.11040 found 267.11004.



methyl 2-diazo-4-methyl-6-phenylhex-3-enoate (**6.6d**)

To a stirred solution of methyl 4-methyl-6-phenylhex-3-enoate (567 mg, 2.6 mmol, 1.0 equiv) and *p*-acetamidobenzenesulfonyl azide (*p*-ABSA) (1.9 g, 7.8 mmol, 3.0 equiv) in acetonitrile (20 mL) under argon atmosphere, DBU (2.4 mL, 15.6 mmol, 6.0 equiv) was added drop-wise at 0 °C. The reaction mixture was then stirring overnight. Then, saturated aqueous ammonium chloride (15 mL) was added. The crude mixture was extracted with pentane (3 x 100 mL), washed by brine (3 x 10 mL), dried over anhydrous $MgSO_4$, concentrated *in vacuo*, and purified by flash chromatography (pentane/diethyl ether = 50/1) to afford the methyl 2-diazo-4-methyl-6-phenylhex-3-enoate (**6.6d**) (*E/Z* = 1.4/1, 425 mg, 67%) as an orange oil.

^{1}H NMR (400 MHz, $CDCl_3$): δ 7.29-7.14 (m, 9.2H, *E/Z* mixture), 5.45 (s, 0.72H, *Z* isomer), 5.42 (s, 1H, *E* isomer), 3.75 (s, 4.9H, *E/Z* mixture), 2.74 (t, *J* = 8.0 Hz, 2H, *E* isomer), 2.69 (t, *J* = 8.0 Hz, 1.4H, *Z* isomer), 2.42 (t, *J* = 8.8 Hz, 2H, *E* isomer), 2.30 (t, *J* = 8.8 Hz, 1.4H, *Z* isomer), 1.89 (s, 2.1H, *Z* isomer), 1.70 (s, 3H, *E* isomer); ^{13}C NMR (100 MHz, $CDCl_3$) δ 167.0, 141.4, 141.1, 138.4, 137.7, 128.3, 128.2, 128.1, 125.9, 125.8, 107.0, 106.7, 51.9, 41.8, 35.1, 34.5, 33.7, 23.9, 17.5; IR (neat): 3027, 2950, 2073, 1703, 1436, 1287, 1194; HRMS (FTMS+p-NSI) calcd for $C_{14}H_{17}O_2N_2$ $(M+H)^+$ 245.12845 found 245.12845.



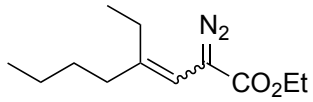
ethyl 2-diazo-4-methyl-5-phenylpent-3-enoate (**6.6e**)

To a solution of ethyl diazoacetate (1.2 equiv, 3.1 mmol, 15% in toluene, 2.36 g) in anhydrous acetonitrile (10 mL), at room temperature, under argon atmosphere, a solution of DBU (3.0 equiv, 7.74 mmol, 1.2 mL) in anhydrous acetonitrile (1.0 mL) and 2-methyl-3-phenylpropanal (2.58 mmol, 383 mg, 1.0 equiv) in anhydrous acetonitrile (2.0 mL) were added successively. The resulting mixture was stirred overnight. The reaction was quenched with saturated sodium bicarbonate (15 mL) and then extracted with diethyl ether (3 x 50 mL). The solvent was removed by evaporation under reduced pressure and the residue was purified by flash chromatography (hexanes/ethyl acetate = 50/1) to give ethyl 2-diazo-3-hydroxy-4-methyl-5-phenylpentanoate (543 mg, 81%).

To a solution of ethyl 2-diazo-3-hydroxy-4-methyl-5-phenylpentanoate (543 mg, 2.1 mmol) and Et_3N (10.5 mmol, 1.5 mL, 5.0 equiv) in dichloromethane (15 mL) at 0 ^oC, was slowly added a solution of $POCl_3$ (966 mg, 6.3 mmol, 3.0 equiv) in dichloromethane (5.0 mL) over 30 minutes. The resulting solution was warmed to room temperature and stirred overnight. The solution was quenched by saturated sodium bicarbonate (15 mL) and extracted with diethyl ether (3 x 50 mL). The crude product was purified by flash chromatography (pentane/diethyl ether = 50/1) to give the ethyl 2-diazo-4-methyl-5-phenylpent-3-enoate (**6.6e**) (*E/Z* = 10/1, 313 mg, 61%).

^1H NMR (400 MHz, $CDCl_3$): δ 7.31-7.12 (m, 5.8H, *E/Z* mixture), 5.64 (s, 0.15H, *Z* isomer), 5.56 (s, 1H, *E* isomer), 4.27 (q, *J* = 8.0 Hz, 2H, *E* isomer), 3.44 (s, 2H, *E* isomer), 3.40 (s, 0.3 H, *Z* isomer), 1.78 (s, 0.5H, *Z* isomer), 1.61 (s, 3H, *E* isomer), 1.29 (t, *J* = 8.0 Hz, 3H, *E* isomer); ^{13}C NMR (100 MHz, $CDCl_3$) δ 166.6, 138.9, 136.7, 128.8,

128.4, 128.3, 126.3, 108.2, 108.1, 60.9, 46.3, 38.7, 23.9, 16.9, 14.4; IR (neat): 3027, 2979, 2072, 1694, 1601, 1494, 1453, 1368, 1275, 1182, 1101, 1027, 850, 729, 698; HRMS (FTMS+p-NSI) calcd for $C_{14}H_{17}O_2N_2$ $(M+H)^+$ 245.12845 found 245.12830.

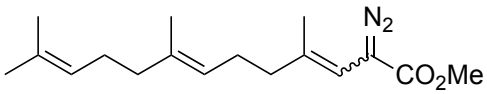


ethyl 2-diazo-4-ethyloct-3-enoate (**6.6f**)

To a solution of ethyl diazoacetate (1.2 equiv, 6.0 mmol, 15% in toluene, 4.6 g) in anhydrous acetonitrile (10 mL), at room temperature, under argon atmosphere, was added successively a solution of DBU (3.0 equiv, 15 mmol, 2.23 mL) in anhydrous acetonitrile (1.0 mL) and 2-ethylhexanal (5.0 mmol, 641 mg, 1.0 equiv) in anhydrous acetonitrile (2.0 mL). The resulting mixture was stirred overnight. The reaction was quenched with saturated sodium bicarbonate (20 mL) and then extracted with diethyl ether (3 x 50 mL). The solvent was removed by evaporation under reduced pressure and the residue was purified by flash chromatography (hexanes/ethyl acetate = 50/1) to give ethyl 2-diazo-4-ethyl-3-hydroxyoctanoate (847 mg, 3.5 mmol, 70%).

To a solution of ethyl 2-diazo-4-ethyl-3-hydroxyoctanoate (847 mg, 3.5 mmol) and Et_3N (17.5 mmol, 2.44 mL, 5 equiv) in dichloromethane (15 mL) at 0 ^oC, was slowly added a solution of $POCl_3$ (1.6 g, 10.5 mmol, 3.0 equiv) in dichloromethane (5 mL) over 30 minutes. The resulting solution was warmed to room temperature and stirred overnight. The solution was quenched by saturated sodium bicarbonate (20 mL) and extracted with diethyl ether (3 x 50 mL). The crude product was purified by flash chromatography (pentane/diethyl ether = 50/1) to give the ethyl 2-diazo-4-ethyloct-3-enoate (**6.6f**) as an orange oil (*E/Z* = 10/1, 533 mg, 68%).

^{1}H NMR (400 MHz, $CDCl_3$): δ 5.37 (s, 1H), 4.26 (q, J = 8.0 Hz, 2H), 2.18-2.11 (m, 2H), 2.08-2.01 (m, 2H), 1.45-1.27 (m, 7H), 1.08-0.97 (m, 3H), 0.91 (t, J = 8.0 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ166.7, 143.9, 143.8, 105.2, 104.6, 60.7, 36.6, 30.8, 30.2, 30.1, 23.9, 22.7, 22.2, 14.2, 13.7, 13.6, 12.4, 12.3; IR (neat): 2962, 2932, 2874, 2072, 1702, 1464, 1369, 1275, 1178, 1117, 1090, 736; HRMS (FTMS+p-NSI) calcd for $C_{12}H_{20}O_2N_2Na$ $(M+Na)^+$ 247.14170 found 247.14138

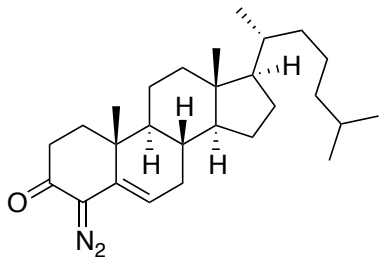


methyl 2-diazo-4,8,12-trimethyltrideca-3,7,11-trienoate (**6.6g**)

To a stirred solution of methyl 4,8,12-trimethyltrideca-3,7,11-trienoate (164.2 mg, 1.0 mmol, 1.0 equiv) and *p*-acetamidobenzenesulfonyl azide (*p*-ABSA) (1.22 g, 5.0 mmol, 5.0 equiv) in dry acetonitrile (10 mL) under argon atmosphere, DBU (1.5 mL, 10 mmol, 10.0 equiv) was added drop-wise at 0 °C. The reaction mixture was then stirred overnight. Then, saturated aqueous ammonium chloride (20 mL) was added. The crude mixture was extracted with pentane (3 x 50 mL), washed by brine (3 x 10 mL), dried over anhydrous $MgSO_4$, concentrated *in vacuo*, and chromatographed (pentane/diethyl ether = 50/1) to afford the methyl 2-diazo-4,8,12-trimethyltrideca-3,7,11-trienoate (**6.6g**) (151 mg, 52%) as a red oil.

^{1}H NMR (400 MHz, $CDCl_3$): δ 5.42 (s, 1H), 5.11-5.07 (m, 2H), 3.78 (s, 3H), 2.16-1.85 (m, 8H), 1.69-1.59 (m, 12H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 167.3, 154.8, 139.3, 139.2, 138.6, 138.5, 136.1, 135.9, 135.8, 135.7, 135.4, 131.6, 131.3, 124.2, 124.1, 123.9, 123.8, 123.3, 123.1, 119.2, 106.6, 106.5, 106.2, 52.0, 51.3, 40.3, 40.0, 39.6, 35.9, 33.2, 32.9, 31.9, 29.7, 26.6, 26.5, 26.4, 25.9, 25.7, 25.6, 25.4, 23.9, 23.3, 19.3, 17.6, 17.5, 16.0; IR

(neat): 2923, 2855, 2073, 1708, 1436, 1285, 1194, 1108; HRMS (FTMS+p-NSI) calcd for $C_{17}H_{27}O_2N_2$ $(M+H)^+$ 291.20670 found 291.20671.



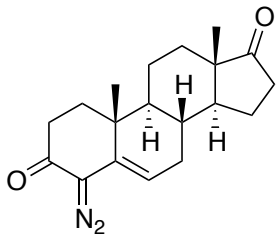
(8*S*,9*S*,10*R*,13*R*,14*S*,17*R*)-4-diazo-10,13-dimethyl-17-((*R*)-6-methylheptan-2-yl) 4,7,8,9,10,11,12,13,14,15,16,17-dodecahydro-1H-cyclopenta[a]phenanthren-3(2H)-one (**6.8**)

To a stirred solution of the cholesterol (1.94 g, 5.0 mmol, 1.0 equiv) in dichloromethane (80 mL) at room temperature, a few drops a saturated sodium bicarbonate were added, followed by addition of Dess-Martin oxidant (5.3g, 12.5 mmol, 2.5 equiv) in several portions over 20 minutes. Then, the reaction was stirred at room temperature for 2.0 hours, and was quenched by a solution of sodium bicarbonate (50 mL). The crude mixture was extracted with ether (3 x 100 mL), washed by brine (3 x 20 mL), dried over anhydrous $MgSO_4$, concentrated *in vacuo*, and chromatographed (pentane/diethyl ether = 50/1 to 20/1) to afford the ketone product (1.3g, 3.4 mmol, 68%).

To a solution of the ketone product (1.3 g, 3.4 mmol, 1.0 equiv) in dry dichromethane (80 mL) at 0 °C under argon atmosphere, was added *p*-acetamidobenzenesulfonyl azide (*p*-ABSA) (8.3 g, 34 mmol, 10.0 equiv), followed DBU (10 mL, 68 mmol, 20 equiv), which was added drop-wise at 0 °C under argon atmosphere. The reaction mixture was then stirred overnight. Then, saturated aqueous ammonium chloride (30 mL) was added. The

crude mixture was extracted with ether (3 x 50 mL), washed by brine (3 x 10 mL), dried over anhydrous $MgSO_4$, concentrated *in vacuo*, and chromatographed (pentane/diethyl ether = 50/1) to afford the (**6.8**) (348.5 mg, 25%) as an orange solid.

^{1}H NMR (400 MHz, $CDCl_3$): δ 5.24-5.22 (m, 1H), 2.60-2.50 (m, 2H), 2.27-2.19 (dt, *J* = 5.2, 18.4 Hz, 1H), 1.88-1.00 (m, 25H), 0.91 (d, *J* = 6.0 Hz, 3H), 0.83 (d, *J* = 6.8 Hz, 1H), 0.68 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 178.7, 128.4, 116.5, 69.9, 59.6, 56.4, 55.9, 47.9, 42.2, 39.4, 39.3, 36.8, 36.0, 35.7, 33.9, 31.7, 31.3, 28.1, 27.9, 24.1, 23.7, 22.8, 22.5, 21.2, 20.7, 18.6, 11.8; IR (neat): 2947, 2867, 2062, 1602, 1346, 1286; HRMS (FTMS+p-NSI) calcd for $C_{27}H_{42}ON_2Na$ $(M+Na)^+$ 433.31894 found 433.31859.



(8*R*,9*S*,10*R*,13*S*,14*S*)-4-diazo-10,13-dimethyl-7,8,9,10,11,12,13,14,15,16-decahydro-1H-cyclopenta[a]phenanthrene-3,17(2H,4H)-dione (**6.10**)

To a stirred solution of (+)-dehydsroisoandrosterone (2.88 g, 10.0 mmol, 1.0 equiv) in dichloromethane (100 mL) at room temperature, a few drops a saturated sodium bicarbonate was added, followed by addition of Dess-Martin oxidant (10.6 g, 25 mmol, 2.5 equiv) in several portions in 30 minutes. Then, the reaction was stirred at room temperature for 1.5 hours, and was quenched by a solution of sodium bicarbonate (20 mL). The crude mixture was extracted with ether (3 x 50 mL), washed by brine (3 x 10 mL), dried over anhydrous $MgSO_4$, concentrated *in vacuo*, and chromatographed

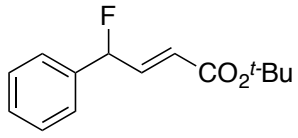
(pentane/diethyl ether = 50/1 to 20/1) to afford the ketone product (2.22 g, 7.8 mmol, 78%).

To a solution of the ketone product (2.22 g, 7.8 mmol, 1.0 equiv) in dry acetonitrile (100 mL) 0 °C under argon atmosphere, was added 3-(azidosulfonyl)benzoic acid (5.3 g, 23.4 mmol, 3.0 equiv) was added in one pot, followed by addition of DBU (5.8 mL, 39 mmol, 5.0 equiv) drop-wise at 0 °C under argon atmosphere. The reaction mixture was then stirring over 2.0 hours at 0 °C. Then, saturated aqueous ammonium chloride (20 mL) was added. The crude mixture was extracted with ether (3 x 50 mL), washed by brine (3 x 10 mL), dried over anhydrous $MgSO_4$, concentrated *in vacuo*, and chromatographed (pentane/diethyl ether = 50/1) to afford the product (**6.10**) as a yellow solid (1.5 g, 62%). ^{1}H NMR (400 MHz, $CDCl_3$): δ 5.04-5.02 (m, 1H), 2.33-2.15 (m, 4H), 1.97-1.56 (m, 7H), 147-0.99 (m, 6H), 0.94 (s, 3H), 0.74 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 220.4, 192.5, 129.8, 114.2, 72.6, 51.6, 48.5, 47.6, 35.9, 35.6, 33.5, 32.4, 31.4, 31.2, 30.0, 21.9, 20.6, 19.5, 13.8; IR (neat): 2945, 2867, 2078, 1739, 1633, 1339, 1264, 1229, 1142; HRMS (FTMS+p-APCI) calcd for $C_{19}H_{25}O_2N_2$ $(M+H)^+$ 313.19105 found 313.19071.

General procedure for silver catalyzed fluorination of vinylcarbenoids

An oven-dried 35 mL heavy wall cylindrical and round bottom vessels containing a Teflon-coated oval stir bar was fitted with a rubber septum and allowed to cool to room temperature under vacuum. At room temperature, silver acetate (6.6 mg, 10 mol%) was added and the flask, wrapped with aluminum foil to avoid light, was connected to a vacuum line *via* a needle inserted through the septum. The flask was evacuated then back-filled with argon. This process was repeated three times. Et_3N-3HF in dry

dichloromethane (2.0 mL) is introduced *via* syringe under a positive argon pressure. Then, to the refluxing reaction mixtures, diazo compound (0.4 mmol) was added drop-wise *via* syringe over 1.0 hour under argon atmosphere, and the syringe was rinsed with dry dichloromethane (0.5-1.0 mL) and then transferred to the reaction. The resulting solution was refluxed for another one hour. The oil bath was removed and the suspension was cooled to room temperature and was quenched by saturated sodium bicarbonate and extracted with diethyl ether (4 x 50 mL). The combined organic solvent was removed by evaporation under reduced pressure and the crude products were purified (hexanes/ethyl acetate) by flash chromatography.

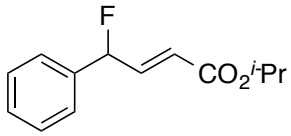


(*E*)-*tert*-butyl 4-fluoro-4-phenylbut-2-enoate (**6.2**)

Prepared according to the general procedure for silver acetate-catalyzed fluorination of vinylcarbenoids using (*E*)-*tert*-butyl 2-diazo-4-phenylbut-3-enoate (**6.1**) (0.4 mmol, 97.6 mg, 1.0 equiv) and Et_3N-3HF (322 mg, 5.0 equiv). The crude residue was analyzed by ^1H NMR and purified by flash column chromatography (hexanes/ethyl acetate = 50/1) to afford the product (**6.2**) as a colorless oil (85.1 mg, 90%).

^1H NMR (400 MHz, $CDCl_3$): δ 7.44-7.35 (m, 5H), 6.96 (ddd, J = 4.8, 16.0, 19.0 Hz, 1H), 6.11-6.10 (m, 0.5H), 6.08-6.06 (m, 1H), 5.95-5.93 (m, 0.5H), 1.50 (s, 9H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 165.0, 142.8 (d, ^2J = 22.3 Hz), 137.5 (d, ^2J = 20.1 Hz), 129.1, 128.8, 126.6 (d, ^3J = 5.2 Hz), 123.4 (^3J = 9.7 Hz), 91.9 (d, ^1J = 173.4 Hz), 80.9, 28.0; ^{19}F NMR (376 MHz, $CDCl_3$) δ -173.3 (q, J = 22.3, 47.8 Hz); IR (neat): 2979, 1714, 1660, 1368,

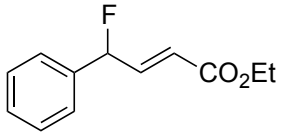
1309, 1254, 1151, 978; HRMS (FTMS+p-NSI) calcd for $C_{14}H_{17}O_2FNa$ $(M+Na)^+$ 259.11048 found 259.11055.



(*E*)-isopropyl 4-fluoro-4-phenylbut-2-enoate (**6.5a**)

Prepared according to the general procedure for silver acetate-catalyzed fluorination of vinylcarbenoids using (*E*)-isopropyl 2-diazo-4-phenylbut-3-enoate (**6.4a**) (0.4 mmol, 92.0 mg, 1.0 equiv) and Et_3N-3HF (322 mg, 5.0 equiv). The crude residue was analyzed by ^1H NMR and purified by flash column chromatography (hexanes/ethyl acetate = 50/1) to afford the product (**6.5a**) as a colorless oil (81.6 mg, 92%).

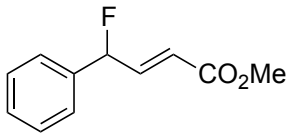
^1H NMR (400 MHz, $CDCl_3$): δ 7.44-7.36 (m, 5H), 7.04 (ddd, J = 4.4, 15.6, 18.8 Hz, 1H), 6.16 (dt, J = 1.6, 15.6 Hz, 1H), 6.03 (dq, J = 1.6, 4.4, 47.2 Hz, 1H), 5.12-5.06 (m, 1H), 1.28 (d, J = 8.0 Hz, 6H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 165.3, 143.2 (d, ^2J = 22.3 Hz), 136.8 (d, ^2J = 20.1 Hz), 129.2, 128.8, 126.6 (d, ^3J = 5.2 Hz), 122.0 (d, ^3J = 10.4 Hz), 91.8 (d, ^1J = 174.1 Hz), 68.2, 21.8; ^{19}F NMR (376 MHz, $CDCl_3$) δ -173.7 (q, J = 47.8, 19.2 Hz); IR (neat): 2927, 2850, 1726, 1665, 1450, 1436, 1310, 1272, 1169, 1040, 981; HRMS (FTMS+p-NSI) calcd for $C_{13}H_{15}O_2FNa$ $(M+Na)^+$ 245.09483 found 245.09478.



(*E*)-ethyl 4-fluoro-4-phenylbut-2-enoate (**6.5b**)

Prepared according to the general procedure for silver acetate-catalyzed fluorination of vinylcarbenoids using (*E*)-ethyl 2-diazo-4-phenylbut-3-enoate (**6.4b**) (0.4 mmol, 86.4 mg, 1.0 equiv) and Et_3N-3HF (322 mg, 5.0 equiv). The crude residue was analyzed by ^1H NMR and purified by flash column chromatography (hexanes/ethyl acetate = 50/1) to afford the product (**6.5b**) as a colorless oil (76.3 mg, 92%).

^1H NMR (400 MHz, $CDCl_3$): δ 7.44-7.35 (m, 5H), 7.06 (ddd, J = 4.4, 16.0, 20.0 Hz, 1H), 6.19 (dt, J = 1.6, 15.6 Hz, 1H), 6.03 (dq, J = 2.0, 4.8, 47.2 Hz, 1H), 4.25-4.20 (m, 2H), 1.31 (t, J = 7.6 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 165.8, 144.0 (d, ^2J = 21.6 Hz), 136.7 (d, ^2J = 20.1 Hz), 129.2, 128.8, 126.6 (d, ^3J = 5.9 Hz), 121.5 (d, ^3J = 10.4 Hz), 91.8 (d, ^1J = 174.2 Hz), 60.7, 14.2; ^{19}F NMR (376 MHz, $CDCl_3$) δ -173.7 (q, J = 47.8, 19.2 Hz); IR (neat): 2984, 1721, 1663, 1304, 1268, 1177, 979; HRMS (FTMS+p-NSI) calcd for $C_{12}H_{13}O_2FNa$ $(M+Na)^+$ 231.07918 found 231.07912.

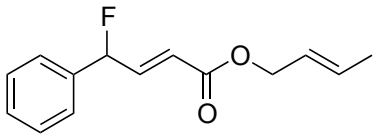


(*E*)-methyl 4-fluoro-4-phenylbut-2-enoate (**6.5c**)

Prepared according to the general procedure for silver acetate-catalyzed fluorination of vinylcarbenoids using ((*E*)-methyl 2-diazo-4-phenylbut-3-enoate (**6.4c**) (0.4 mmol, 80.8 mg, 1.0 equiv) and Et_3N-3HF (322 mg, 5.0 equiv). The crude residue was analyzed by ^1H NMR and purified by flash column chromatography (hexanes/ethyl acetate = 50/1) to afford the product (**6.5c**) as a colorless oil (73.2 mg, 94%).

^1H NMR (400 MHz, $CDCl_3$): δ 7.44-7.35 (m, 5H), 7.06 (ddd, J = 4.4, 16.0, 20.0 Hz, 1H), 6.20 (dt, J = 1.6, 15.6 Hz, 1H), 6.03 (dq, J = 2.0, 4.8, 47.2 Hz, 1H), 3.77 (s, 3H); ^{13}C

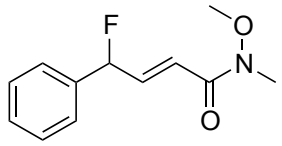
NMR (100 MHz, $CDCl_3$) δ 166.2, 144.3 (d, ^2J = 21.6 Hz), 136.6 (d, ^2J = 20.1 Hz), 129.2, 128.8, 126.6 (d, ^3J = 5.2 Hz), 120.9 (d, ^3J = 10.5 Hz), 91.7 (d, ^1J = 174.1 Hz), 51.8; ^{19}F NMR (376 MHz, $CDCl_3$) δ -173.9 (q, J = 47.4, 18.8 Hz); IR (neat): 2953, 1727, 1667, 1436, 1308, 1278, 979; HRMS (FTMS+p-NSI) calcd for $C_{11}H_{11}O_2FNa$ $(M+Na)^+$ 217.06353 found 217.06347.



(*E*)-(*E*)-but-2-en-1-yl 4-fluoro-4-phenylbut-2-enoate (**6.5d**)

Prepared according to the general procedure for silver acetate-catalyzed fluorination of vinylcarbenoids using (*E*)-(*E*)-but-2-en-1-yl 2-diazo-4-phenylbut-3-enoate (**6.4d**) (0.4 mmol, 96.8 mg, 1.0 equiv) and Et_3N-3HF (322 mg, 5.0 equiv). The crude residue was analyzed by ^{1}H NMR and purified by flash column chromatography (hexanes/ethyl acetate = 50/1) to afford the product (**6.5d**) as a colorless oil (79.6 mg, 85%).

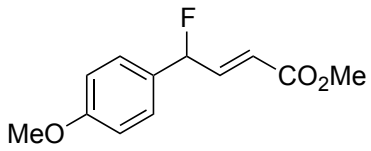
^{1}H NMR (400 MHz, $CDCl_3$): δ 7.43-7.31 (m, 5H), 7.06 (ddd, J = 4.0, 15.6, 19.2 Hz, 1H), 6.19 (d, J = 15.6 Hz, 1H), 6.08 (dd, J = 4.4, 47.6 Hz, 1H), 5.86-5.79 (m, 1H), 5.66-5.89 (m, 1H), 4.60 (d, J = 6.8 Hz, 2H), 1.74 (d, J = 6.4 Hz, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 165.9, 144.5 (d, ^2J = 22.3 Hz), 136.9 (d, ^2J = 20.0 Hz), 132.1, 129.5, 129.1, 126.9 (d, ^3J = 5.2 Hz), 125.0, 121.6 (d, ^3J = 9.7 Hz), 91.1 (d, ^1J = 174.1 Hz), 65.8, 18.0; ^{19}F NMR (376 MHz, $CDCl_3$) δ -173.8 (q, J = 47.4, 18.8 Hz); IR (neat): 2919, 1722, 1662, 1455, 1305, 1264, 1168, 968, 697; HRMS (FTMS+p-NSI) calcd for $C_{14}H_{15}O_2FNa$ $(M+Na)^+$ 257.09483 found 257.09474.



(*E*)-4-fluoro-*N*-methoxy-*N*-methyl-4-phenylbut-2-enamide (**6.5e**)

Prepared according to the general procedure for silver acetate-catalyzed fluorination of vinylcarbenoids using (*E*)-2-diazo-*N*-methoxy-*N*-methyl-4-phenylbut-3-enamide (**6.4e)** (0.4 mmol, 92.4 mg, 1.0 equiv) and Et_3N-3HF (322 mg, 5.0 equiv). The crude residue was analyzed by ^1H NMR and purified by flash column chromatography (hexanes/ethyl acetate = 50/1) to afford the product (**6.5e**) as a colorless oil (53.5 mg, 60%).

^1H NMR (400 MHz, $CDCl_3$): δ 7.43-7.31 (m, 5H), 7.08 (ddd, J = 4.4, 15.6, 20.0 Hz, 1H), 6.79 (d, J = 15.6 Hz, 1H), 6.08 (dq, J = 1.6, 4.4, 47.6 Hz, 1H), 3.74 (s, 3H), 3.27 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 165.7, 142.7 (d, ^2J = 20.8 Hz), 136.9 (d, ^2J = 19.3 Hz), 129.1, 128.7, 126.7 (d, ^3J = 6.0 Hz), 118.6 (d, ^3J = 9.7 Hz), 92.3 (d, ^1J = 174.1 Hz), 61.9, 32.3; ^{19}F NMR (376 MHz, $CDCl_3$) δ -172.7 (q, J = 47.4, 20.7 Hz); IR (neat): 2937, 1667, 1637, 1456, 1418, 1384, 1179, 1119, 1003, 701; HRMS (FTMS+p-NSI) calcd for $C_{12}H_{15}O_2FN$ $(M+H)^+$ 224.10813 found 224.10800.

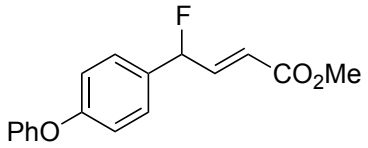


(*E*)-methyl 4-fluoro-4-(4-methoxyphenyl)but-2-enoate (**6.5f**)

Prepared according to the general procedure for silver acetate-catalyzed fluorination of vinylcarbenoids using (*E*)-methyl 2-diazo-4-(4-methoxyphenyl)but-3-enoate (**6.4f)** (0.4 mmol, 92.8 mg, 1.0 equiv) and Et_3N-3HF (322 mg, 5.0 equiv). Dry product (**6.5f)** was

unstable over 2.0 hours even under vacuum condition and was also decomposed upon on silica gel column (yield was based on NMR using dibromomethane as internal standard, 96%).

^{1}H NMR (400 MHz, $CDCl_3$): δ 7.29 (d, J = 8.0 Hz, 2H), 7.06 (ddd, J = 4.0, 16.0, 20.0 Hz, 1H), 6.93 (d, J = 8.0 Hz, 1H), 6.19 (dt, J = 1.6, 16.0 Hz, 1H), 5.98 (dq, J = 1.6, 4.4, 47.6 Hz, 1H), 3.83 (s, 3H), 3.77 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 166.6, 160.7, 144.8 (d, ^{2}J = 23.1 Hz), 129.3, 128.9, 120.9 (d, ^{3}J = 9.7 Hz), 114.3, 91.8 (d, ^{1}J = 173.4 Hz), 55.6, 52.1; ^{19}F NMR (376 MHz, $CDCl_3$) δ -168.2 (q, J = 47.4, 18.8 Hz); IR (neat): 2953, 2840, 1726, 1662, 1611, 1514, 1437, 1306, 1251, 1173, 1033, 834; HRMS (FTMS+p-NSI) calcd for $C_{12}H_{14}O_3F$ $(M+H)^+$ 225.09215 found 225.09108.

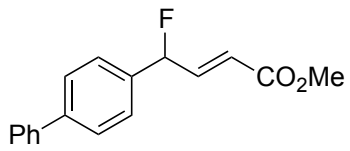


(*E*)-methyl 4-fluoro-4-(4-phenoxyphenyl)but-2-enoate (**6.5g**)

Prepared according to the general procedure for silver acetate-catalyzed fluorination of vinylcarbenoids using (*E*)-methyl 2-diazo-4-(4-phenoxyphenyl)but-3-enoate (**6.4g**) (0.4 mmol, 117.6 mg, 1.0 equiv) and Et_3N-3HF (322 mg, 5.0 equiv). Product (**6.5g**) was unstable on silica gel column (yield was based on NMR using dibromomethane as internal standard, 95%).

^{1}H NMR (400 MHz, $CDCl_3$): δ 7.39-7.31 (m, 4H), 7.17-7.11 (m, 1H), 7.10-7.02 (m, 5H), 6.21 (dt, J = 1.6, 15.6 Hz, 1H), 6.01 (dq, J = 1.6, 4.4, 47.6 Hz, 1H), 3.83 (s, 3H), 3.78 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 166.3, 158.4, 156.5, 144.3 (d, ^{2}J = 22.3 Hz), 130.1 (d, ^{2}J = 20.1 Hz), 129.9, 128.6 (d, ^{3}J = 5.2 Hz), 123.8, 121.0 (d, ^{3}J = 9.6 Hz), 119.3,

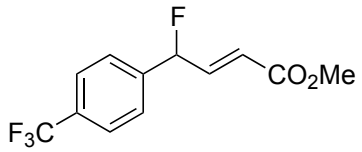
118.7, 92.4 (d, ^{1}J = 173.4 Hz), 51.9; ^{19}F NMR (376 MHz, $CDCl_3$) δ -170.3 (q, J = 47.8, 19.2 Hz); IR (neat): 2951, 1727, 1664, 1589, 1507, 1489, 1239, 1168, 1074, 980, 870; HRMS (FTMS+p-NSI) calcd for $C_{17}H_{15}O_3FNa$ $(M+Na)^+$ 309.08974 found 309.08970.



(*E*)-methyl 4-([1,1'-biphenyl]-4-yl)-4-fluorobut-2-enoate (**6.5h**)

Prepared according to the general procedure for silver acetate-catalyzed fluorination of vinylcarbenoids using (*E*)-methyl 4-([1,1'-biphenyl]-4-yl)-2-diazobut-3-enoate (**6.4h**) (0.4 mmol, 111.24 mg, 1.0 equiv) and Et_3N-3HF (322 mg, 5.0 equiv). The crude residue was analyzed by ^{1}H NMR and purified by flash column chromatography (hexanes/ethyl acetate = 50/1) to afford the product (**6.5h**) as a white solid (93.6 mg, 87%).

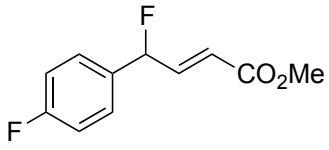
Mp: 60-62 ^{o}C; ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.66-7.59 (m, 4H), 7.50-7.37 (m, 5H), 7.12 (ddd, J = 4.8, 15.8, 19.6 Hz, 1H), 6.25 (d, J = 15.8 Hz, 1H), 6.01 (dd, J = 3.6, 46.8 Hz, 1H), 3.79 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 166.2, 144.3 (d, ^{2}J = 22.3 Hz), 142.3, 140.3, 135.5 (d, ^{2}J = 20.1 Hz), 128.8, 127.7, 127.6, 127.1 (d, ^{3}J = 3.0 Hz), 121.0 (d, ^{3}J = 10.4 Hz), 91.6 (d, ^{1}J = 174.1 Hz), 51.8; ^{19}F NMR (376 MHz, $CDCl_3$) δ -173.3 (q, J = 45.9, 17.3 Hz); IR (neat): 3031, 2951, 1727, 1664, 1487, 1436, 1307, 1273, 1171, 1077, 979, 766, 698; HRMS (FTMS+p-NSI) calcd for $C_{17}H_{15}O_2FNa$ $(M+Na)^+$ 293.09483 found 293.09475.



(*E*)-methyl 4-fluoro-4-(4-(trifluoromethyl)phenyl)but-2-enoate (**6.5i**)

Prepared according to the general procedure for silver acetate-catalyzed fluorination of vinylcarbenoids using (*E*)-methyl 2-diazo-4-(4-(trifluoromethyl)phenyl)but-3-enoate (**6.4i**) (0.4 mmol, 108.0 mg, 1.0 equiv) and Et_3N-3HF (322 mg, 5.0 equiv). The crude residue was analyzed by ^1H NMR and purified by flash column chromatography (hexanes/ethyl acetate = 50/1) to afford the product (**6.5i**) as a white solid (66.0 mg, 63%).

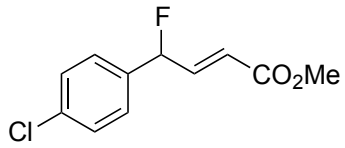
Mp: 42-44 ^oC; ^1H NMR (400 MHz, $CDCl_3$): δ 7.68 (d, J = 8.0 Hz, 2H), 7.49 (d, J = 8.0 Hz, 2H), 7.03 (ddd, J = 4.0, 16.0, 19.6 Hz, 1H), 6.20 (dt, J = 1.6, 15.8 Hz, 1H), 6.09 (dd, J = 3.6, 46.8 Hz, 1H), 3.78 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 165.9, 143.2 (^2J = 21.6 Hz), 140.5 (^2J = 20.8 Hz), 131.3 (q, J = 32.8 Hz), 126.6 (d, ^3J = 5.9 Hz), 125.8 (d, ^3J = 3.7 Hz), 121.8 (d, ^3J = 10.4 Hz), 90.9 (d, ^1J = 175.6 Hz), 51.9; ^{19}F NMR (376 MHz, $CDCl_3$) δ -63.2 (s), -177.7 (q, J = 45.9, 19.2 Hz); IR (neat): 2956, 1727, 1665, 1621, 1438, 1417, 1324, 1167, 1126, 1067, 979, 844; HRMS (FTMS+p-NSI) calcd for $C_{12}H_{11}O_2F_4$ $(M+H)^+$ 263.06897 found 263.06900.



(*E*)-methyl 4-fluoro-4-(4-fluorophenyl)but-2-enoate (**6.5j**)

Prepared according to the general procedure for silver acetate-catalyzed fluorination of vinylcarbenoids using (*E*)-methyl 2-diazo-4-(4-fluorophenyl)but-3-enoate (**6.4j**) (0.4 mmol, 88.0 mg, 1.0 equiv) and Et_3N-3HF (322 mg, 5.0 equiv). The crude residue was analyzed by ^1H NMR and purified by flash column chromatography (hexanes/ethyl acetate = 50/1) to afford the product (**6.5j**) as a light yellow oil (73.6 mg, 87%).

^1H NMR (400 MHz, $CDCl_3$): δ 7.36-7.32 (m, 2H), 7.12-6.99 (m, 3H), 6.19 (dt, J = 1.6, 15.6 Hz, 1H), 6.01 (dq, J = 4.4, 46.8 Hz, 1H), 3.78 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 166.2, 163.1 (d, ^1J = 247.0 Hz), 143.9 (d, ^2J = 21.6 Hz), 132.4 (d, ^2J = 23.8 Hz), 128.82, 128.77, 128.74, 128.69, 121.2 (d, ^3J = 10.4 Hz), 115.8 (d, ^2J = 21.5 Hz), 91.1 (d, ^1J = 174.1 Hz), 51.9; ^{19}F NMR (376 MHz, $CDCl_3$) δ -112.2 (m), -171.5 (q, J = 47.3, 18.8 Hz); IR (neat): 2956, 1728, 1662, 1513, 1437, 1279, 1227, 1172, 839; HRMS (FTMS+p-NSI) calcd for $C_{11}H_{11}O_2F_2$ $(M+H)^+$ 213.07216 found 213.07205.

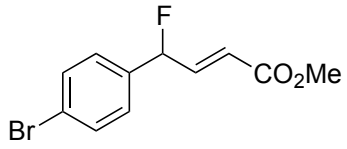


(*E*)-methyl 4-(4-chlorophenyl)-4-fluorobut-2-enoate (**6.5k**)

Prepared according to the general procedure for silver acetate-catalyzed fluorination of vinylcarbenoids using (*E*)-methyl 4-(4-chlorophenyl)-2-diazobut-3-enoate (**6.4k**) (0.4 mmol, 94.4 mg, 1.0 equiv) and Et_3N-3HF (322 mg, 5.0 equiv). The crude residue was analyzed by ^1H NMR and purified by flash column chromatography (hexanes/ethyl acetate = 50/1) to afford the product (**6.5k**) as a light yellow oil (77.6 mg, 85%).

^1H NMR (400 MHz, $CDCl_3$): δ 7.35 (d, J = 8.0, 2H), 7.26 (d, J = 8.0, 2H), 6.99 (ddd, J = 4.4, 16.0, 20.0 Hz, 1H), 6.15 (dt, J = 1.6, 15.6 Hz, 1H), 5.97 (dd, J = 4.4, 46.8 Hz, 1H),

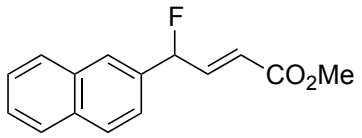
3.74 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 166.0, 143.6 (d, ^2J = 21.5 Hz), 135.1 (d, ^2J = 19.3 Hz), 129.1, 128.0, 127.9, 121.3 (d, ^3J = 9.6 Hz), 91.0 (d, ^1J = 174.9 Hz), 51.9; ^{19}F NMR (376 MHz, $CDCl_3$) δ -174.0 (q, J = 47.8, 19.2 Hz); IR (neat): 2952, 1723, 1663, 1597, 1493, 1436, 1274, 1197, 1079, 1016, 978, 830; HRMS (FTMS+p-NSI) calcd for $C_{11}H_{10}O_2ClFNa$ $(M+Na)^+$ 251.02456 found 251.02459.



(*E*)-methyl 4-(4-bromophenyl)-4-fluorobut-2-enoate (**6.5l**)

Prepared according to the general procedure for silver acetate-catalyzed fluorination of vinylcarbenoids using (*E*)-methyl 4-(4-bromophenyl)-2-diazobut-3-enoate (**6.4l**) (0.4 mmol, 111.9 mg, 1.0 equiv) and Et_3N-3HF (322 mg, 5.0 equiv). The crude residue was analyzed by ^{1}H NMR and purified by flash column chromatography (hexanes/ethyl acetate = 50/1) to afford the product (**6.5l**) as a colorless oil (96.5 mg, 89%).

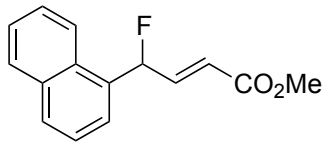
^{1}H NMR (400 MHz, $CDCl_3$): δ 7.54 (d, J = 8.0, 2H), 7.24 (d, J = 8.0, 2H), 7.01 (ddd, J = 4.4, 16.0, 20.0 Hz, 1H), 6.18 (dt, J = 1.6, 15.6 Hz, 1H), 5.98 (dq, J = 2.0, 4.4, 47.2 Hz, 1H), 3.77 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 166.0, 143.6 (d, ^2J = 22.3 Hz), 135.6 (d, ^2J = 20.1 Hz), 132.0, 128.2 (d, ^3J = 5.9 Hz), 121.4 (d, ^3J = 9.7 Hz), 123.4, 91.0 (d, ^1J = 174.9 Hz), 51.9; ^{19}F NMR (376 MHz, $CDCl_3$) δ -174.5 (q, J = 47.8, 19.2 Hz); IR (neat): 2951, 1727, 1663, 1593, 1449, 1436, 1310, 1277, 1171, 1071, 1012, 979, 829; HRMS (FTMS+p-NSI) calcd for $C_{11}H_{10}O_2BrFNa$ $(M+Na)^+$ 294.97404 found 294.97400.



(*E*)-methyl 4-fluoro-4-(naphthalen-2-yl)but-2-enoate (**6.5m**)

Prepared according to the general procedure for silver acetate-catalyzed fluorination of vinylcarbenoids using (*E*)-methyl 2-diazo-4-(naphthalen-2-yl)but-3-enoate (**6.4m**) (0.4 mmol, 100.8 mg, 1.0 equiv) and Et_3N-3HF (322 mg, 5.0 equiv). The crude residue was analyzed by ^1H NMR and purified by flash column chromatography (hexanes/ethyl acetate = 50/1) to afford the product (**6.5m**) as a colorless oil (78.0 mg, 80%).

^1H NMR (400 MHz, $CDCl_3$): δ 7.91-7.83 (m, 4H), 7.55-7.52 (m, 2H), 7.47-7.44 (m, 1H), 7.16 (ddd, J = 3.6, 16.0, 18.8 Hz, 1H), 6.28-6.13 (m, 3H), 3.78 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 166.3, 144.3 (d, ^2J = 21.6 Hz), 133.9 (d, ^2J = 19.3 Hz), 133.5, 133.0, 128.9, 128.2, 127.8, 126.8, 126.6, 126.2 (d, ^3J = 7.4 Hz), 123.8 (d, ^3J = 4.5 Hz), 121.2 (d, ^3J = 10.4 Hz), 91.9 (d, ^1J = 174.9 Hz), 51.9; ^{19}F NMR (376 MHz, $CDCl_3$) δ -173.5 (q, J = 47.8, 19.2 Hz); IR (neat): 3058, 2951, 1725, 1663, 1509, 1436, 1307, 1273, 1171, 1076, 1018, 980, 820; HRMS (FTMS+p-NSI) calcd for $C_{15}H_{13}O_2$ $(M\text{-}HF+H)^+$ 225.09155 found 225.09085.

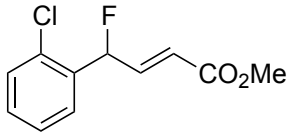


(*E*)-methyl 4-fluoro-4-(naphthalen-1-yl)but-2-enoate (**6.5n**)

Prepared according to the general procedure for silver acetate-catalyzed fluorination of vinylcarbenoids using (*E*)-methyl 2-diazo-4-(naphthalen-1-yl)but-3-enoate (**6.4n**) (0.4

mmol, 100.8 mg, 1.0 equiv) and Et_3N-3HF (322 mg, 5.0 equiv). The crude residue was analyzed by ^1H NMR and purified by flash column chromatography (hexanes/ethyl acetate = 50/1) to afford the product (**6.5n**) as a colorless oil (81.2 mg, 83%).

^1H NMR (400 MHz, $CDCl_3$): δ 8.05 (d, J = 8.0 Hz, 1H), 7.91 (t, J = 8.0 Hz, 2H), 7.61-7.48 (m, 4H), 7.28 (ddd, J = 4.4, 16.0, 18.8 Hz, 1H), 6.73 (dq, J = 2.0, 3.6, 46.4 Hz, 1H), 6.28 (dt, J = 1.6, 15.6 Hz, 1H), 3.77 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 166.3, 144.3 (d, ^2J = 21.5 Hz), 133.8, 132.3 (d, ^2J = 17.9 Hz), 130.3, 130.0, 128.9, 126.8, 126.1, 125.3, 125.2, 123.2, 121.6 (d, ^3J = 9.7 Hz), 89.9 (d, ^1J = 174.1 Hz), 51.8; ^{19}F NMR (376 MHz, $CDCl_3$) δ -175.9 (q, J = 45.9, 18.8 Hz); IR (neat): 2951, 1725, 1663, 1511, 1436, 1309, 1274, 1173, 978, 781; HRMS (FTMS+p-NSI) calcd for $C_{15}H_{14}O_2F$ $(M+H)^+$ 245.09723 found 245.09728.

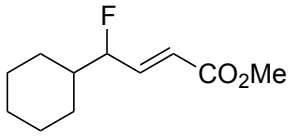


(*E*)-methyl 4-(2-chlorophenyl)-4-fluorobut-2-enoate (**6.5o**)

Prepared according to the general procedure for silver acetate-catalyzed fluorination of vinylcarbenoids using (*E*)-methyl 4-(2-chlorophenyl)-2-diazobut-3-enoate (**6.4o**) (0.4 mmol, 94.4 mg, 1.0 equiv) and Et_3N-3HF (322 mg, 5.0 equiv). The crude residue was analyzed by ^1H NMR and purified by flash column chromatography (hexanes/ethyl acetate = 50/1) to afford the product (**6.5o**) as a colorless oil (67.4 mg, 74%).

^1H NMR (400 MHz, $CDCl_3$): δ 7.48-7.29 (m, 4H), 7.06 (ddd, J = 4.0, 15.6, 19.2 Hz, 1H), 6.44 (dq, J = 1.6, 4.0, 46.0 Hz, 1H), 6.19 (dt, J = 1.6, 15.6 Hz, 1H), 3.73 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 166.2, 142.8 (d, ^2J = 21.6 Hz), 134.6 (d, ^2J = 21.6 Hz), 131.8

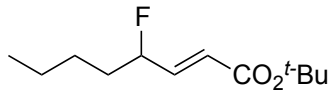
(d, ^{3}J = 5.2 Hz), 130.2, 129.7, 127.4, 127.3, 121.3 (d, ^{3}J = 10.5 Hz), 88.3 (d, ^{1}J = 174.8 Hz), 51.9; ^{19}F NMR (376 MHz, $CDCl_3$) δ -182.6 (q, J = 45.9, 19.2 Hz); IR (neat): 2952, 1727, 1663, 1478, 1437, 1308, 1276, 1196, 1172, 979, 754; HRMS (FTMS+p-NSI) calcd for $C_{11}H_{11}O_2FCl$ $(M+H)^+$ 229.04261 found 229.04249.



(*E*)-methyl 4-cyclohexyl-4-fluorobut-2-enoate (**6.5p**)

Prepared according to the general procedure for silver acetate-catalyzed fluorination of vinylcarbenoids using (*E*)-methyl 4-cyclohexyl-2-diazobut-3-enoate (**6.4p**) (0.4 mmol, 94.4 mg, 1.0 equiv) and Et_3N-3HF (322 mg, 5.0 equiv). The crude residue was analyzed by ^{1}H NMR and purified by flash column chromatography (hexanes/ethyl acetate = 50/1) to afford the product (**6.5p**) as a colorless oil (68.0 mg, 85%).

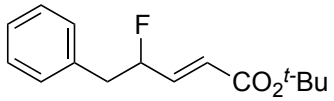
^{1}H NMR (400 MHz, $CDCl_3$): δ 6.91 (ddd, J = 4.0, 15.6, 20.8 Hz, 1H), 6.06 (d, J = 15.6 Hz, 1H), 4.85 (dt, J = 4.0, 47.6 Hz, 1H), 3.76 (s, 3H), 1.78-1.63 (m, 6H), 1.27-1.05 (m, 5H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 166.4, 144.4 (d, ^{2}J = 19.4 Hz), 121.1 (d, ^{3}J = 11.1 Hz), 94.9 (d, ^{1}J = 174.9 Hz), 51.7, 42.2 (d, ^{2}J = 20.1 Hz), 28.2 (d, ^{3}J = 3.7 Hz), 27.2 (d, ^{3}J = 5.2 Hz), 26.1, 25.8, 25.7; ^{19}F NMR (376 MHz, $CDCl_3$) δ -190.8 (m); IR (neat): 2927, 2850, 1726, 1665, 1450, 1436, 1310, 1272, 1169, 1040, 981; HRMS (FTMS+p-NSI) calcd for $C_{11}H_{18}O_2F$ $(M+H)^+$ 201.12853 found 201.12846.



(*E*)-*tert*-butyl 4-fluorooct-2-enoate (**6.5q**)

Prepared according to the general procedure for silver acetate-catalyzed fluorination of vinylcarbenoids using (*E*)-*tert*-butyl 2-diazoo-3-enoate (**6.4q**) (0.4 mmol, 89.6 mg, 1.0 equiv) and Et_3N-3HF (322 mg, 5.0 equiv). The crude residue was analyzed by ^1H NMR and purified by flash column chromatography (hexanes/ethyl acetate = 50/1) to afford the product (**6.5q**) as a colorless oil (74.3 mg, 86%).

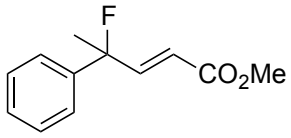
^1H NMR (400 MHz, $CDCl_3$): δ 6.80 (ddd, J = 4.4, 15.6, 19.2 Hz, 1H), 5.97 (dm, J = 15.6 Hz, 1H), 5.14-4.98 (m, 1H), 1.78-1.66 (m, 2H), 1.51 (s, 9H), 1.47-1.33 (m, 4H), 0.92 (t, ^3J = 7.2 Hz); ^{13}C NMR (100 MHz, $CDCl_3$) δ 165.3, 143.9 (d, ^2J = 18.6 Hz), 122.8 (d, ^3J = 11.1 Hz), 91.4 (d, ^1J = 171.8 Hz), 80.7, 34.4 (d, ^2J = 20.8 Hz), 28.1, 26.6 (d, ^3J = 3.8 Hz), 22.4, 13.8; ^{19}F NMR (376 MHz, $CDCl_3$) δ -183.8 (m); IR (neat): 2960, 2935, 2874, 1717, 1664, 1458, 1368, 1315, 1285, 1154, 980; HRMS (FTMS+p-NSI) calcd for $C_{12}H_{22}O_2F$ $(M+H)^+$ 217.15983 found 217.15974.



(*E*)-*tert*-butyl 4-fluoro-5-phenylpent-2-enoate (**6.5r**)

Prepared according to the general procedure for silver acetate-catalyzed fluorination of vinylcarbenoids using (*E*)-*tert*-butyl 2-diazo-5-phenylpent-3-enoate (**6.4r**) (0.4 mmol, 103.2 mg, 1.0 equiv) and Et_3N-3HF (322 mg, 5.0 equiv). The crude residue was analyzed by ^1H NMR and purified by flash column chromatography (hexanes/ethyl acetate = 50/1) to afford the product (**6.5**) as a colorless oil (81.1 mg, 81%).

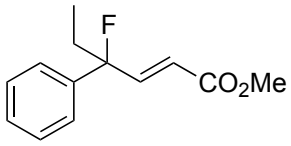
^{1}H NMR (400 MHz, $CDCl_3$): δ 7.34-7.14 (m, 5H), 6.82 (ddd, J = 4.4, 15.6, 20.0 Hz, 1H), 5.99 (dm, J = 15.6 Hz, 1H), 5.31-5.15 (m, 1H), 3.09-2.90 (m, 2H), 1.47 (s, 9H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 165.1, 142.9 (d, ^2J = 18.6 Hz), 135.7 (d, ^3J = 4.4 Hz), 129.4, 128.5, 126.9, 123.5 (d, ^3J = 10.4 Hz), 91.7 (d, ^1J = 175.6 Hz), 80.8, 41.4 (d, ^2J = 22.3 Hz), 28.0; ^{19}F NMR (376 MHz, $CDCl_3$) δ -182.0 (m); IR (neat): 2978, 1713, 1662, 1455, 1367, 1312, 1285, 1255, 1149, 1089, 977, 699; HRMS (FTMS+p-NSI) calcd for $C_{15}H_{20}O_2F$ $(M+H)^+$ 251.14418 found 251.14402.



(*E*)-methyl 4-fluoro-4-phenylpent-2-enoate (**6.7a**)

Prepared according to the general procedure for silver acetate-catalyzed fluorination of vinylcarbenoids using (*E*)-methyl 2-diazo-4-phenylpent-3-enoate (**6.6a**) (0.4 mmol, 86.4 mg, 1.0 equiv) and Et_3N-3HF (322 mg, 5.0 equiv). The crude residue was analyzed by ^{1}H NMR and purified by flash column chromatography (hexanes/ethyl acetate = 50/1) to afford the product (**6.7a**) as a colorless oil (75.6 mg, 91%).

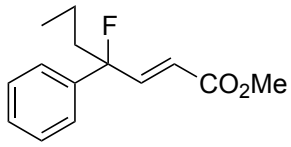
^{1}H NMR (400 MHz, $CDCl_3$): δ 7.40-7.32 (m, 5H), 7.13 (dd, J = 15.6, 20.8 Hz, 1H), 6.13 (d, J = 15.6 Hz, 1H), 3.76 (s, 3H), 1.84 (d, J = 20.8 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 166.6, 149.1 (d, ^2J = 23.1 Hz), 141.3 (d, ^2J = 22.3 Hz), 128.6, 128.2, 124.5 (d, ^3J = 8.2 Hz), 118.8 (d, ^3J = 10.4 Hz), 95.1 (d, ^1J = 175.6 Hz), 51.8, 26.5 (d, ^2J = 24.6 Hz); ^{19}F NMR (376 MHz, $CDCl_3$) δ -146.4 (m); IR (neat): 2989, 2952, 1724, 1663, 1496, 1435, 1375, 1309, 1279, 1196, 1172, 763, 698; HRMS (FTMS+p-APCI) calcd for $C_{12}H_{14}O_2F$ $(M+H)^+$ 209.09723 found 209.09717.



(*E*)-methyl 4-fluoro-4-phenylhex-2-enoate (**6.7b**)

Prepared according to the general procedure for silver acetate-catalyzed fluorination of vinylcarbenoids using (*E*)-Methyl 2-diazo-4-phenylhex-3-enoate (**6.6b**) (0.4 mmol, 92.0 mg, 1.0 equiv) and Et_3N-3HF (322 mg, 5.0 equiv). The crude residue was analyzed by ^1H NMR and purified by flash column chromatography (hexanes/ethyl acetate = 50/1) to afford the product (**6.7b**) as a colorless oil (72.8 mg, 82%).

^1H NMR (400 MHz, $CDCl_3$): δ 7.42-7.31 (m, 5H), 7.12 (dd, J = 15.6, 21.6 Hz, 1H), 6.14 (d, J = 15.6 Hz, 1H), 3.75 (s, 3H), 2.16-2.04 (m, 2H), 0.92 (t, J = 6.8 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 166.7, 148.4 d, ^2J = 20.9 Hz), 140.6 (d, ^2J = 22.3 Hz), 128.5, 127.9, 124.5 (^3J = 8.9 Hz), 119.1 (d, ^3J = 10.5 Hz), 97.6 (d, ^1J = 180.8 Hz), 51.7, 32.7 (d, ^2J = 23.8 Hz), 7.41 (d, ^3J = 4.4 Hz); ^{19}F NMR (376 MHz, $CDCl_3$) δ -163.2 (q, J = 22.6, 45.5 Hz); IR (neat): 2977, 2949, 1728, 1661, 1436, 1311, 1274, 1195, 1172, 698; HRMS (FTMS+p-NSI) calcd for $C_{13}H_{15}O_2FNa$ $(M+Na)^+$ 245.09483 found 245.09485.

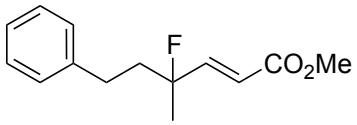


(*E*)-methyl 4-fluoro-4-phenylhept-2-enoate (**6.7c**)

Prepared according to the general procedure for silver acetate-catalyzed fluorination of vinylcarbenoids using (*E*)-methyl 2-diazo-4-phenylhept-3-enoate (**6.6c**) (0.4 mmol, 97.6 mg, 1.0 equiv) and Et_3N-3HF (322 mg, 5.0 equiv). The crude residue was analyzed by ^1H

NMR and purified by flash column chromatography (hexanes/ethyl acetate = 50/1) to afford the product (**6.7c**) as a colorless oil (72.8 mg, 82%).

^{1}H NMR (400 MHz, $CDCl_3$): δ 7.42-7.31 (m, 5H), 7.12 (dd, *J* = 15.6, 21.6 Hz, 1H), 6.13 (d, *J* = 15.6 Hz, 1H), 3.75 (s, 3H), 2.09-1.98 (m, 2H), 1.44-1.32 (m, 2H), 0.92 (t, *J* = 7.2 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 166.7, 148.6 (^{2}J = 21.6 Hz), 141.1 (d, ^{2}J = 22.4 Hz), 128.5, 127.8, 124.4 (d, ^{3}J = 8.9 Hz), 118.9 (d, ^{3}J = 11.2 Hz), 97.5 (d, ^{1}J = 180.1 Hz), 51.7, 41.9 (d, ^{2}J = 23.0 Hz), 16.5 (d, ^{3}J = 10.1 Hz), 14.0; ^{19}F NMR (376 MHz, $CDCl_3$) δ -160.8 (q, *J* = 22.9, 45.5 Hz); IR (neat): 2961, 2875, 1724, 1661, 1495, 14351309, 1275, 1194, 1171, 979, 919, 852, 763, 698; HRMS (FTMS+p-NSI) calcd for $C_{14}H_{17}O_2FNa$ $(M+Na)^+$ 259.11048 found 259.11030.

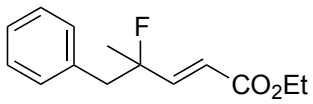


(*E*)-methyl 4-fluoro-4-methyl-6-phenylhex-2-enoate (**6.7d**)

Prepared according to the general procedure for sliver acetate-catalyzed fluorination of vinylcarbenoids using methyl 2-diazo-4-methyl-6-phenylhex-3-enoate (**6.6d**) (0.4 mmol, 97.6 mg, 1.0 equiv) and Et_3N-3HF (322 mg, 5.0 equiv). The crude residue was analyzed by ^{1}H NMR and purified by flash column chromatography (hexanes/ethyl acetate = 50/1) to afford the product (**6.7d**) as a colorless oil (84.1 mg, 89%).

^{1}H NMR (400 MHz, $CDCl_3$): δ 7.30-7.16 (m, 5H), 6.93 (dd, *J* = 15.6, 21.6 Hz, 1H), 6.11 (d, *J* = 15.6 Hz, 1H), 3.77 (s, 3H), 2.77-2.57 (m, 2H), 2.13-1.84 (m, 2H), 1.51 (d, *J* = 21.6 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 166.7, 149.1 (d, ^{2}J = 20.8 Hz), 141.2, 128.5, 128.2, 126.0, 119.4 (d, ^{3}J = 10.4 Hz), 95.2 (d, ^{1}J = 175.6 Hz), 51.8, 41.7 (d, ^{2}J = 22.3

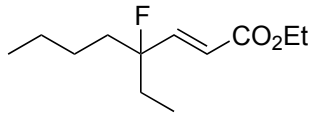
Hz), 29.7 (d, ^{3}J = 3.7 Hz), 25.5 (d, ^{2}J = 24.5 Hz); ^{19}F NMR (376 MHz, $CDCl_3$) δ -153.1 (m); IR (neat): 3027, 2951, 1726, 1664, 1497, 1435, 1313, 1274, 1198, 1165, 698; HRMS (FTMS+p-NSI) calcd for $C_{14}H_{17}O_2FNa$ $(M+Na)^+$ 259.11048 found 259.11034.



(*E*)-ethyl 4-fluoro-4-methyl-5-phenylpent-2-enoate (**6.7e**)

Prepared according to the general procedure for silver acetate-catalyzed fluorination of vinylcarbenoids using ethyl 2-diazo-4-methyl-5-phenylpent-3-enoate (**6.6e**) (0.4 mmol, 97.6 mg, 1.0 equiv) and Et_3N-3HF (322 mg, 5.0 equiv). The crude residue was analyzed by ^{1}H NMR and purified by flash column chromatography (hexanes/ethyl acetate = 50/1) to afford the product (**6.7e**) as a colorless oil (75.5 mg, 80%).

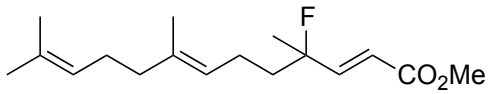
^{1}H NMR (400 MHz, $CDCl_3$): δ 7.32-7.19 (m, 5H), 6.94 (dd, *J* = 15.6, 20.8 Hz, 1H), 5.99 (d, *J* = 15.6 Hz, 1H), 4.20 (q, *J* = 7.2 Hz, 2H), 3.09-2.93 (m, 2H), 1.42 (d, *J* = 21.6 Hz, 3H), 1.29 (t, *J* = 7.2 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 166.2, 148.8 (d, ^{2}J = 21.1 Hz), 134.9, 130.4, 128.9, 128.2, 126.9, 119.8 (d, ^{3}J = 10.4 Hz), 95.0 (d, ^{1}J = 177.1 Hz), 60.5, 46.2 (d, ^{2}J = 23.1 Hz), 24.5 (d, ^{2}J = 23.8 Hz), 14.2; ^{19}F NMR (376 MHz, $CDCl_3$) δ -149.3 (m); IR (neat): 2983, 2933, 1720, 1662, 1454, 1367, 1306, 1282, 1180, 1091, 1032, 982, 700; HRMS (FTMS+p-NSI) calcd for $C_{14}H_{18}O_2F$ $(M+H)^+$ 237.12853 found 237.12953.



(*E*)-ethyl 4-ethyl-4-fluorooct-2-enoate (**6.7f**)

Prepared according to the general procedure for silver acetate-catalyzed fluorination of vinylcarbenoids using ethyl 2-diazo-4-ethyloct-3-enoate (**6.6f**) (0.4 mmol, 89.6 mg, 1.0 equiv) and Et_3N-3HF (322 mg, 5.0 equiv). The crude residue was analyzed by ^{1}H NMR and purified by flash column chromatography (hexanes/ethyl acetate = 50/1) to afford the product (**6.7f**) as a colorless oil (76.0 mg, 88%).

^{1}H NMR (400 MHz, $CDCl_3$): δ 6.80 (dd, J = 15.6, 20.8 Hz, 1H), 6.03 (d, J = 15.6 Hz, 1H), 4.21 (q, J = 7.2 Hz, 2H), 1.83-1.59 (m, 4H), 1.40-1.23 (m, 8H), 0.93-0.87 (m, 7H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 166.3, 148.4 (d, ^2J = 20.1 Hz), 120.4 (d, ^3J = 10.4 Hz), 97.9 (d, ^1J = 178.0 Hz), 60.5, 37.9 (d, ^2J = 23.1 Hz), 31.4 (d, ^2J = 23.8 Hz), 25.3 (d, ^3J = 4.5 Hz), 22.8, 14.0 (d, ^2J = 29.8 Hz), 7.50 (d, ^3J = 5.2 Hz); ^{19}F NMR (376 MHz, $CDCl_3$) δ -163.2 (m); IR (neat): 2959, 2941, 2874, 1722, 1662, 1465, 1367, 1305, 1268, 1179, 1038, 983; HRMS (FTMS+p-NSI) calcd for $C_{12}H_{21}O_2FNa$ $(M+Na)^+$ 239.14178 found 239.14178.

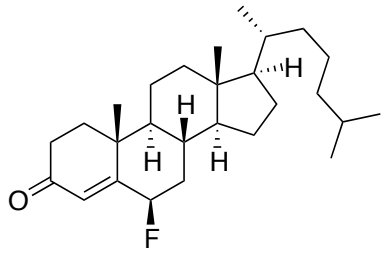


(2*E*)-methyl 4-fluoro-4,8,12-trimethyltrideca-2,7,11-trienoate (**6.7g**)

Prepared according to the general procedure for silver acetate-catalyzed fluorination of vinylcarbenoids using methyl 2-diazo-4,8,12-trimethyltrideca-3,7,11-trienoate **6.6g** (0.4 mmol, 116.0 mg, 1.0 equiv) and Et_3N-3HF (322 mg, 5.0 equiv). The crude residue was

analyzed by ^{1}H NMR and purified by flash column chromatography (hexanes/ethyl acetate = 50/1) to afford the product (**6.7g**) as a colorless oil (95.9 mg, 85%).

^{1}H NMR (400 MHz, $CDCl_3$): δ 6.94-6.84 (ddm, J = 15.6, 20.8 Hz, 1H), 6.07-6.02 (dm, J = 15.6 Hz, 1H), 5.09-5.05 (m, 2H), 3.76 (s, 3H), 2.07-1.94 (m, 6H), 1.82-1.58 (m, 11H), 1.48-1.42 (d, J = 21.6 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 166.7, 149.5 (d, ^{2}J = 20.1 Hz), 136.0 (d, ^{3}J = 8.9 Hz), 131.6, 131.3, 124.2, 124.1, 123.9, 123.0, 119.0 (d, ^{3}J = 10.4 Hz), 95.2 (d, ^{1}J = 174.9 Hz), 51.7, 40.2, 40.0, 39.0, 39.6, 31.8, 26.6, 26.4, 25.7, 25.6, 25.4 (d, ^{2}J = 24.5 Hz), 23.3, 22.04, 21.99, 21.92, 21.87, 17.58 (d, ^{3}J = 10.4 Hz), 15.9; ^{19}F NMR (376 MHz, $CDCl_3$) δ -152.3 (m); IR (neat): 2969, 2915, 2874, 1729, 1664, 1435, 1376, 1312, 1272, 1197, 1165, 979, 907; HRMS (FTMS+p-NSI) calcd for $C_{17}H_{28}O_2F$ $(M+H)^+$ 283.20678 found 283.20668.

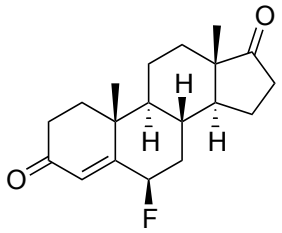


(6*R*,8*S*,9*S*,10*R*,13*R*,14*S*,17*R*)-6-fluoro-10,13-dimethyl-17-((R)-6-methylheptan-2-yl)-6,7,8,9,10,11,12,13,14,15,16,17-dodecahydro-1H-cyclopenta[a]phenanthren-3(2H)-one (**6.9**)

Prepared according to the general procedure using sliver acetate-catalyzed fluorination of vinylcarbenoids using steroid diazo (**6.8**) (0.4 mmol, 116.0 mg, 1.0 equiv) and Et_3N-3HF (644 mg, 10.0 equiv) with silver triflate as catalyst. The reaction was refluxing under argon for another 2.0 hours after diazo addition and the crude residue was analyzed by ^{1}H

NMR and purified by flash column chromatography (hexanes/ethyl acetate = 80/1 to 50/1) to afford the product (**6.9**) as a white solid (90.1 mg, 56%).

Mp: 81-83 ^{o}C; ^{1}H NMR (400 MHz, $CDCl_3$): δ 5.87 (d, J = 4.8 Hz, 1H), 4.99 (dt, J = 2.8, 48.4 Hz, 1H), 2.60-2.50 (m, 1H), 2.42-2.37 (m, 1H), 2.24-2.17 (m, 1H), 2.09-2.04 (m, 1H), 1.94-1.82 (m, 2H), 1.77-1.69 (m, 1H), 1.62-1.47 (m, 4H), 1.43-0.99 (m, 17H), 0.91 (d, J = 6.4 Hz, 3H), 0.86 (d, J = 6.4 Hz, 6H), 0.733 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 200.0, 162.1 (d, ^{2}J = 12.6 Hz), 128.2 (d, ^{3}J = 8.9 Hz), 93.5 (d, ^{1}J = 165.1 Hz), 56.0, 55.7, 53.2, 42.4, 39.4, 37.8, 37.4, 37.2, 36.8, 36.0, 35.7, 34.2, 29.9, 28.1, 27.9, 23.9, 23.8, 22.8, 22.5, 20.8, 18.6, 18.3, 11.9; ^{19}F NMR (376 MHz, $CDCl_3$) δ -165.7 (m); IR (neat): 2935, 2868, 1686, 1467, 1380, 1331, 1267, 1191; HRMS (FTMS+p-APCI) calcd for $C_{27}H_{44}OF$ $(M+H)^+$ 403.33707 found 403.33640.



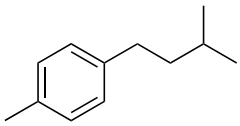
(6*R*,8*R*,9*S*,10*R*,13*S*,14*S*)-6-fluoro-10,13-dimethyl-7,8,9,10,11,12,13,14,15,16-decahydro-1H-cyclopenta[a]phenanthrene-3,17(2H,6H)-dione (**6.11**)

Prepared according to the general procedure using silver acetate -catalyzed fluorination of vinylcarbenoids using steroid diazo (**6.10**) (0.4 mmol, 124.8 mg, 1.0 equiv) and Et_3N-3HF (644 mg, 10.0 equiv) with silver triflate as catalyst. The reaction was refluxing under argon for another 2.0 hours after diazo addition and the crude residue was analyzed by ^{1}H NMR and purified by flash column chromatography (hexanes/ethyl acetate = 80/1 to 50/1) to afford the product (**6.11**) as a white solid (72.8 mg, 60%).

Mp: 130-133 ^{o}C; ^{1}H NMR (400 MHz, $CDCl_3$): δ 5.90 (d, J = 4.8 Hz, 1H), 5.05 (dt, J = 2.8, 48.4 Hz, 1H), 2.62-2.31 (m, 5H), 2.18-1.63 (m, 10H), 1.34 (s, 3H), 1.11-0.97 (m, 2H), 0.96 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 220.1, 199.6, 161.1 (d, ^{2}J = 12.0 Hz), 128.6 (d, ^{3}J = 8.9 Hz), 93.0 (d, ^{1}J = 166.6 Hz), 53.2, 50.6, 47.6, 37.8, 36.8, 36.2, 35.9, 35.6, 34.1, 31.1, 29.6, 21.6, 20.1, 18.4, 13.7; ^{19}F NMR (376 MHz, $CDCl_3$) δ -166.1 (m); IR (neat): 2945, 1737, 1684, 1455, 1377, 1329, 1268, 1229, 1012; HRMS (FTMS+p-APCI) calcd for $C_{19}H_{26}O_2F$ $(M+H)^+$ 305.19113 found 305.19109.

Experimental Data for Chapter VII:

Procedure for non-commercially available C-H substrates synthesis



1-isopentyl-4-methylbenzene (**7.17**)

To a stirred solution of aluminum trichloride (7.0 g, 0.5 equiv) in toluene (250 mL), 3-methylbutanoyl chloride (12.0 g, 100 mmol, 1.0 equiv) was added drop-wise at 0 °C. The reaction mixture was then stirred overnight. Then, saturated aqueous sodium bicarbonate was added. The crude mixture was extracted with ether (3 x 100 mL), washed by brine (3 x 20 mL), dried over anhydrous $MgSO_4$, concentrated *in vacuo*, and the crude mixture was used without further purification.

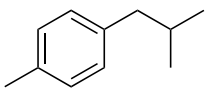
To the crude mixture in methanol (100 mL) at 0 °C, was added sodium borohydride (9.5 g, 2.5 equiv) over 30 minutes. Then, the reaction went to room temperature overnight. Then, saturated aqueous ammonium chloride (50 mL) was added. The crude mixture was extracted with ether (3 x 100 mL), washed by brine (3 x 20 mL), dried over anhydrous

$MgSO_4$, concentrated *in vacuo*, and the crude mixture was purified by flash column chromatography (hexanes/ethyl acetate = 30/1) to afford the alcohol product.

To the obtained alcohol product in toluene (150 mL), was added *p*-toluenesulfonic acid (catalytic amount). The resulting mixture was heated to 90-100 °C. The reaction was monitored by TLC technique until the starting material was consumed completely. Then, water was added. The crude mixture was extracted with ether (3 x 100 mL), washed by saturated sodium bicarbonate (3 x 10 mL) and brine (3 x 10 mL), dried over anhydrous $MgSO_4$, concentrated *in vacuo*, and the crude mixture was purified by flash column chromatography (hexanes) to afford the alkene product (7.0 g, 44 mmol).

To the alkene (7.0 g, 44 mmol) in ethanol (150 mL), was added palladium on activated carbon (5%, 0.1 equiv, 1.18 g). The reaction solution was purged with a hydrogen balloon for 15 minutes and then went overnight under hydrogen atmosphere. Then, the reaction was filtered over a short path of Celite, concentrated *in vacuo*, and the crude mixture was purified by flash column chromatography (hexanes) to afford the final product (**7.17**) (4.2 g, 25% 4 steps).

^{1}H NMR (400 MHz, $CDCl_3$): δ 7.10 (br, 4H), 2.59 (t, J = 8.0 Hz, 2H), 2.33 (s, 3H), 1.63-1.55 (m, 1H), 1.55-1.47 (m, 2H), 0.94 (d, J = 6.0 Hz, 6H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 139.9, 134.9, 128.9, 128.2, 41.0, 33.3, 27.7, 22.5, 20.9; IR (neat): 2953, 2925, 2868, 1516, 1467, 1384, 1366, 802; HRMS (FTMS+p-NSI) calcd for $C_{12}H_{19}$ $(M+H)^+$163.14813 found 163.14815.



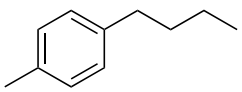
1-isobutyl-4-methylbenzene (**7.27a**)

To a 250 mL flask was charged with isobutyraldehyde (15 mmol, 1.1 g, 1.5 equiv) in dry ether (50 mL), tosyl magnesium bromide (0.5 M, 1.0 equiv, 10 mmol, 20 mL) was added over 1 hour under a dry argon atmosphere at 0 $^{\circ}$C, the reaction went to room temperature overnight. The reaction was quenched by saturated ammonium chloride solution (15 mL) and was extracted with ether (3 x 100 mL). The crude mixture was purified by flash column chromatography (hexanes/ethyl acetate = 30/1) to afford the alcohol product.

The alcohol product obtained was dissolved in toluene (100 mL), and *p*-toluenesulfonic acid (catalytic amount) was added and the solution was heated to 90-100 $^{\circ}$C until the alcohol disappeared from TLC analysis. The reaction was then cooled to room temperature and quenched by saturated ammonium chloride solution (20 mL), extracted by ether (3 x 100 mL), dried over $MgSO_4$. Then, the reaction was filtered, concentrated in *vacuo* to give the alkene crude product.

The crude alkene product was dissolved in ethyl alcohol (80 mL), palladium on activated carbon (5%, 118 mg) was added, and the solution was then purged with a hydrogen balloon for 15 minutes and went overnight under hydrogen atmosphere. Then, the reaction was filtered over a short path of Celite, concentrated *in vacuo*, and the crude mixture was purified by flash column chromatography (hexanes) to afford the final product (**7.27a**) (769 mg, 52%, 3 steps).

^{1}H NMR (400 MHz, $CDCl_3$): δ 7.33-7.26 (m, 4H), 2.68 (d, J = 8.0 Hz, 2H), 2.55 (s, 3H), 2.12-2.05 (m, 1H), 1.15 (d, J = 6.4 Hz, 6H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 138.5, 134.9, 128.9, 128.8, 45.1, 30.3, 22.4, 20.9; IR (neat, cm^{-1}): 2954, 2922, 2868, 1515, 1465, 1383, 1366, 834, 791, 752; HRMS (FTMS+p-NSI) calcd for $C_{11}H_{17}$ $(M+H)^{+}$149.13248 found 149.13247.



1-butyl-4-methylbenzene (**7.27b**)

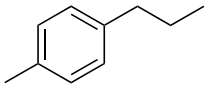
In a 250 mL flask was charged with butyraldehyde (10 mmol, 721 mg) in dry THF (50 mL), tosyl magnesium bromide (0.5 M, 1.2 equiv, 12 mmol, 24 mL) wad added over 1 hour under a dry argon atmosphere at 0 °C, the reaction was warmed to room temperature overnight. The reaction was quenched by saturated ammonium chloride solution (20 mL) and was extracted with ether (3 x 100 mL). The crude mixture was purified by flash column chromatography (hexanes/ethyl acetate = 30/1) to afford the alcohol product.

The alcohol product obtained was dissolved in toluene (100 mL), and *p*-toluenesulfonic acid (catalytic amount) was added and the solution was heated to 90-100 °C until the alcohol disappeared from TLC analysis. The reaction was then cooled to room temperature and quenched by saturated ammonium chloride solution (20 mL), extracted by ether (3 x 100 mL), dried over $MgSO_4$. Then, the reaction was filtered, concentrated in *vacuo* to give the alkene crude product.

The crude alkene product was dissolved in ethyl alcohol (80 mL), palladium on activated carbon (5%, 118 mg) was added, and the solution was then purged with hydrogen balloon for 15 minutes and then went overnight under hydrogen atmosphere. Then, the reaction was filtered over a short path of Celite, concentrated *in vacuo*, and the crude mixture was purified by flash column chromatography (hexanes) to afford the final product (**7.26b**) (681 mg, 42%, 3 steps). The NMR spectrum is consistent with previously reported data.[19]

[19] Ackermann, L.; Kapdi, A. R.; Schulzke, C. *Org. Lett.* **2010**, *12*, 2298.

^{1}H NMR (400 MHz, $CDCl_3$): δ 7.24 (br, 4H), 2.74 (t, *J* = 8.0 Hz, 2H), 2.48 (s, 3H), 1.80-1.72 (m, 2H), 1.57-1.48 (m, 2H), 1.10 (t, *J* = 8.0 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 139.8, 134.8, 128.9, 128.3, 35.2, 33.8, 22.4, 20.9, 13.9.



1-methyl-4-propylbenzene (**7.27c**)

To a stirred solution of aluminum trichloride (10 g, 75 mmol, 1.5 equiv) in toluene (250 mL), propionyl chloride (4.4 mL, 50 mmol, 1.0 equiv) was added dropwise at 0 °C. The reaction mixture went to room temperature overnight. Then, saturated aqueous sodium bicarbonate (50 mL) was added. The crude mixture was extracted with ether (3 x 100 mL), washed by brine (3 x 10 mL), dried over anhydrous $MgSO_4$, concentrated *in vacuo*, and the crude mixture was used without further purification.

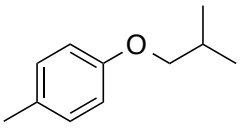
To the crude mixture in dry ether (100 mL) at 0 °C, was added DIBAL (75 mmol, 1M in toluene, 75 mL) over 1.0 hour. Then, the reaction went to room temperature overnight. Then, saturated aqueous ammonium chloride (50 mL) was added. The crude mixture was extracted with ether (3 x 100 mL), washed by brine (3 x 10 mL), dried over anhydrous $MgSO_4$, concentrated *in vacuo*, and the crude mixture was purified by flash column chromatography (hexanes/ethyl acetate = 30/1) to afford alcohol product.

To the obtained alcohol product in toluene (150 mL), was added *p*-toluenesulfonic acid (catalytic amount). The resulting mixture was heated to 90-100 °C. The reaction was monitored by TLC technique until the starting material was consumed completely. Then, saturated ammonium chloride solution (20 mL) was added. The crude mixture was extracted with ether (3 x 100 mL), washed by saturated sodium bicarbonate (3 x 20 mL)

and brine (3 x 10 mL), dried over anhydrous $MgSO_4$, concentrated *in vacuo*, and the crude mixture was purified by flash column chromatography (hexanes) to afford the alkene product.

To the alkene in ethanol (150 mL), was added palladium on activated carbon (5%, 0.1 equiv, 519 mg). The reaction solution was purged with hydrogen balloon for 15 minutes and then went overnight under hydrogen balloon. Then, the reaction was filtered over a short path of Celite, concentrated *in vacuo*, and the crude mixture was purified by flash column chromatography (hexanes) to afford the final product (**7.27c**) (3.2 g, 48% 4 steps). The NMR spectrum is consistent with previously reported data.[20]

^{1}H NMR (400 MHz, $CDCl_3$): δ 7.28-7.20 (m, 4H), 2.70 (t, J = 8.0 Hz, 2H), 2.47 (s, 3H), 1.83-1.74 (m, 1H), 1.10 (t, J = 8.0 Hz, 6H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 139.6, 134.9, 128.9, 128.3, 37.9, 24.7, 21.0, 13.9.



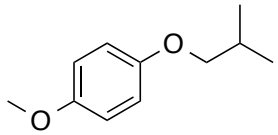
1-isobutoxy-4-methylbenzene (**7.27d**)

In a 250 mL round bottom flask was charged with *p*-cresol (20 mmol, 2.2 g), K_2CO_3 (40 mmol, 5.5 g), 1-iodo-2-methylpropane (30 mmol, 5.52 g) in DMF (50 mL). The mixture was heated at 90-100 °C overnight. Then, the reaction was cooled to room temperature and saturated aqueous ammonium chloride (50 mL) was added. The crude mixture was extracted with ether (3 x 100 mL), washed by brine (3 x 10 mL), dried over anhydrous

[20] Chowdhury, R. R.; Crane, A. K.; Fowler, C.; Kwong, P.; Kozak, C. M. *Chem. Comm.* **2008**, *1*, 94.

$MgSO_4$, concentrated in *vacuo*, and the crude mixture was purified by flash column chromatography (hexanes) to afford the product (**7.27d**) (815 mg, 25%).

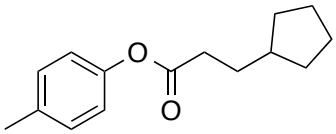
^{1}H NMR (400 MHz, $CDCl_3$): δ 7.19 (d, J = 8.0 Hz, 2H), 6.93 (d, J = 8.0 Hz, 2H), 3.81 (d, J = 8.0 Hz, 2H), 2.41 (s, 3H), 2.25-2.15 (m, 1H), 1.15 (d, J = 8.0 Hz, 6H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 157.1, 129.8, 129.5, 114.3, 28.3, 20.4, 19.2; IR (neat): 2957, 2872, 1615, 1510, 1471, 1394, 1240, 1173, 1038, 817, 804; HRMS (FTMS+p-NSI) calcd for $C_{11}H_{17}O$ $(M+H)^+$ 165.12739 found 165.12732.



1-isobutoxy-4-methoxybenzene (**7.27e**)

To a 100 mL round bottom flask was charged with 4-methoxyphenol (20 mmol, 2.48 g), K_2CO_3 (40 mmol, 5.5 g), 1-iodo-2-methylpropane (30 mmol, 5.52 g) in DMF (50 mL). The mixture was heated at 90-100 °C overnight. Then, the reaction was cooled to room temperature and saturated aqueous ammonium chloride (50 mL) was added. The crude mixture was extracted with ether (3 x 100 mL), washed by brine (3 x 10 mL), dried over anhydrous $MgSO_4$, concentrated in *vacuo*, and the crude mixture was purified by flash column chromatography (hexanes) to afford the product (**7.27e**) (1.62 g, 45%).

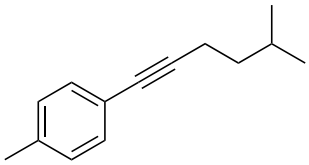
^{1}H NMR (400 MHz, $CDCl_3$): δ 6.89-6.79 (m, 4H), 3.78 (s, 3H), 3.68 (d, J = 8.0 Hz, 2H), 3.81 (d, J = 8.0 Hz, 2H), 2.11-2.01 (m, 1H), 1.01 (d, J = 8.0 Hz, 6H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 153.6, 153.4, 115.3, 114.5, 75.0, 55.6, 28.3, 19.2; IR (neat): 2956, 2907, 2872, 2833, 1506, 1469, 1227, 1179, 1105, 1040, 822, 743; HRMS (FTMS+p-NSI) calcd for $C_{11}H_{17}O_2$ $(M+H)^+$ 181.12231 found 181.12253.



p-tolyl 3-cyclopentylpropanoate (**7.27f**)

In a 500 mL round bottom flask was charged with *p*-cresol (20 mmol, 2.16g) in DCM (100 mL), pyridine (16 mL) and 4-dimethylaminopyridine (240 mg, 0.1 equiv) were added. 3-cyclopentylpropanoyl chloride (3.4 mL, 24 mmol, 1.2 equiv) was added drop-wise at 0 °C under a positive argon pressure. The, the reaction mixture went was warmed to room temperature overnight. The reaction was quenched by 1 N HCl, and was extracted with ether (3 x 100 mL), dried over $MgSO_4$, and concentrated in *vacuo*, and the crude mixture was purified by flash column chromatography (hexanes/ethyl acetate = 50/1) to afford the product (**7.27f**) (4.8 g, >99%).

^{1}H NMR (400 MHz, $CDCl_3$): δ 7.19 (d, J = 8.0 Hz, 2H), 6.99 (d, J = 8.0 Hz, 2H), 2.59 (t, J = 8.0 Hz, 2H), 2.37 (s, 3H), 1.91-1.78 (m, 5H), 1.72-1.55 (m, 4H), 1.23-1.15 (m, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 172.5, 148.4, 135.2, 129.8, 121.1, 39.7, 32.4, 31.0, 25.1, 20.8; IR (neat): 2947, 2865, 1757, 1507, 1453, 1199, 1166, 1124, 1019; HRMS (FTMS+p-NSI) calcd for $C_{15}H_{20}O_2Na$ $(M+Na)^+$ 255.13555 found 255.13521.

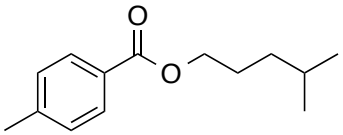


1-methyl-4-(5-methylhex-1-yn-1-yl)benzene (**7.27g**)

In a 250 mL round bottom flask was charged with 4-iodotoluene (20 mmol, 4.36g), 5-methyl-1-hexyne (30 mmol, 2.9g, 1.5 equiv), $Pd(PPh_3)_4$ (2.5 mol%, 578 mg), CuI (5 mol%. 192 mg) under a positive argon pressure, triethyl amine (50 mL) was added and

the reaction mixture was stirred at room temperature overnight. Then, the reaction was quenched by saturated aqueous ammonium chloride (50 mL). The crude mixture was extracted with ether (3 x 100 mL), washed by brine (3 x 10 mL), dried over anhydrous $MgSO_4$, concentrated in *vacuo*, and the crude mixture was purified by flash column chromatography (hexanes/ethyl acetate = 50/1) to afford the product (**7.27g**) (2.83 g, 78%).

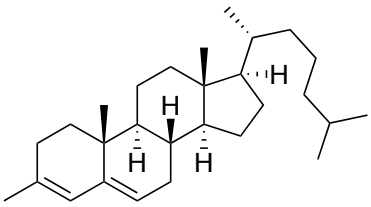
^{1}H NMR (400 MHz, $CDCl_3$): δ 7.29 (d, *J* = 8.0 Hz, 2H), 7.08 (d, *J* = 8.0 Hz, 2H), 2.41 (t, *J* = 7.4 Hz, 2H), 2.34 (s, 3H), 1.79-1.73 (m, 1H), 1.54-1.48 (m, 2H), 0.91 (d, *J* = 8.0 Hz, 6H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 137.3, 131.3, 128.9, 120.9, 89.5, 80.4, 37.7, 27.2, 22.2, 21.3, 17.4; IR (neat): 3028, 2955, 2927, 2868, 1509, 1467, 814; HRMS (FTMS+p-APCI) calcd for $C_{14}H_{19}$ $(M+H)^+$ 187.14813 found 187.14843.



4-methylpentyl 4-methylbenzoate (**7.27h**)

In a 250 mL round bottom flask was charged with 4-methyl-1-pentanol (10 mmol, 1.02 g), in dichloromethane (50 mL), 4-dimethylaminopyridine (122 mg, 0.1 equiv) and pyridine (8 mL) were added and the reaction mixture was cooled to 0 °C. Tosyl chloride (1.9g, 12 mmol, 1.2 equiv) in 5 mL DCM was added dropwise under a positive argon atmosphere. Then, the reaction went to room temperature overnight. The reaction was quenched by 1N HCl, and extracted by ether (3 x 100 mL), washed by brine (3 x 10 mL), dried over anhydrous $MgSO_4$, concentrated in *vacuo*, and the crude mixture was purified by flash column chromatography (hexanes/ethyl acetate = 50/1) to afford the product (**7.27h**) (1.85 g, 84%).

^{1}H NMR (400 MHz, $CDCl_3$): δ 7.94 (d, *J* = 7.6 Hz, 2H), 7.24 (d, *J* = 7.6 Hz, 2H), 4.29 (t, *J* = 7.2 Hz, 2H), 2.42 (s, 3H), 1.81-1.73 (m, 2H), 1.65-1.59 (m, 1H), 1.35-1.29 (m, 2H), 0.92 (d, *J* = 6.4 Hz, 6H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 166.1, 142.8, 129.2, 128.6, 127.5, 64.7, 34.8, 27.4, 26.3, 22.1, 21.1; IR (neat): 2955, 2870, 1715, 1611, 1467, 1270, 1177, 1104, 752; HRMS (FTMS+p-NSI) calcd for $C_{14}H_{20}O_2Na$ $(M+Na)^+$ 243.13555 found 243.13626.



(8*S*,9*S*,10*R*,13*R*,14*S*,17*R*)-3,10,13-trimethyl-17-((*R*)-6-methylheptan-2-yl)-2,7,8,9,10,11,12,13,14,15,16,17-dodecahydro-1H-cyclopenta[a]phenanthrene (**7.43**)

In a 250 mL round-bottom flask was charged with cholesterol (10 mmol, 3.87 g), in DCM (100 mL), a few drops of saturated sodium bicarbonate solution were added, followed by addition of Dess-Martin periodinane (2.2 equiv, 22 mmol, 9.33 g) in several portions within half an hour in air at 0 °C. Then, the reaction was stirred for another 2 hours. The reaction was quenched by saturated sodium bicarbonate solution and (50 mL) and was extracted with dichloromethane (3 x 100 mL), washed by brine (3 x 10 mL), dried over anhydrous $MgSO_4$, concentrated in *vacuo*, and the crude mixture was purified by flash column chromatography (hexanes/ethyl acetate = 30/1) to afford the ketone product (3.25 g, 84%).

The ketone (1.8 mmol, 0.7 g) was dissolved in dry ether (50 mL), MeMgBr (3.0 equiv, 1.0 M in ether, 5.4 mL) was added under argon atmosphere at 0 °C over 1.0 hour, then

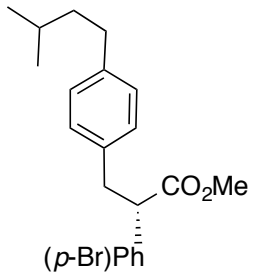
went to room temperature over 2 hours. The reaction was quenched by 1 N HCl and was extracted with ether (3 x 100 mL), washed by brine (3 x 10 mL), dried over anhydrous $MgSO_4$, concentrated in *vacuo*, and the crude mixture was then dissolved in toluene (60 mL), *p*-toluenesulfonic acid (catalytic amount) was added and the solution was heated to 90-100 $^{\circ}$C until the alcohol disappeared from TLC analysis. The reaction was then cooled to room temperature and quenched by saturated ammonium chloride solution (50 mL), extracted by ether (3 x 100 mL), dried over $MgSO_4$, concentrated in *vacuo*, and the crude mixture was purified by flash column chromatography (hexanes) to afford the product **467** as a white solid (426.3 mg, two steps, 62%).

Mp: 65-67 °C; ^{1}H NMR (400 MHz, $CDCl_3$): δ 5.71 (s, 1H), 5.32 (s, 1H), 2.18-2.12 (m, 2H), 2.06-2.01 (m, 2H), 1.98-1.92 (m, 2H), 1.89-1.80 (m, 2H), 1.74 (s, 3H), 1.65-1.52 (m, 4H), 1.42-1.35 (m, 4H), 1.24-1.06 (m, 10H), 0.95-0.93 (m, 6H), 0.90 (d, J = 2.0 Hz, 3H), 0.88 (d, J = 2.0 Hz, 3H), 0.72 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 141.9, 132.9, 124.5, 120.8, 56.9, 56.2, 48.4, 42.4, 39.8, 39.5, 36.2, 35.8, 34.7, 34.2, 31.8, 31.7, 28.3, 28.0, 27.9, 24.2, 23.9, 23.3, 22.8, 22.6, 21.1, 18.9, 18.7, 11.9; IR (neat): 2932, 2866, 2850, 1466, 1443, 1376, 1366, 868, 796, 652; HRMS (FTMS+p-NSI) calcd for $C_{28}H_{47}$ $(M+H)^+$ 383.36723 found 383.36711.

General procedure for selective C–H functionalization

An oven-dried 10 mL round bottom flask containing a Teflon-coated oval stir bar was fitted with a rubber septum and allowed to cool to room temperature under vacuum. At room temperature, alkane substrate and rhodium catalyst were added and the flask

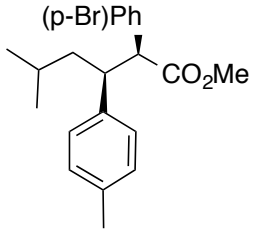
connected with a water condenser, which was connected to a vacuum line *via* a needle inserted through the septum. The flask was evacuated then back-filled with argon (3 times) or flushed with argon for one minute to remove the air in the flask. Dichloromethane (1.0 mL) is introduced *via* syringe under a positive argon pressure. Then, diazo compound (0.4 mmol) in the given solvent was added drop-wise *via* syringe under the given temperature over 1.5 hour under argon atmosphere. The diazo residue was rinsed with the same solvent (0.5 mL) and was transferred into the reaction. The resulting solution was refluxed another 1.5 hour. The oil bath was removed and the reaction was cooled to room temperature, concentrated *in vacuo* and the crude mixture was purified by flash column chromatography (hexanes/ethyl acetate) to afford the product.



methyl (*S*)-2-(4-bromophenyl)-3-(4-isopentylphenyl)propanoate (**7.18**)

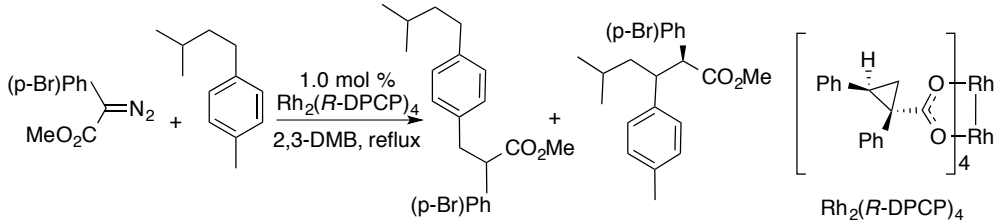
Prepared according to the general procedure for selective C–H functionalization using methyl 2-(4-bromophenyl)-2-diazoacetate (**7.1**) (0.4 mmol, 102 mg, 1.0 equiv), 1-isopentyl-4-methylbenzene (**7.17**) (77.3 mg, 1.2 equiv), Rh_2(*R*-BPCP)$_4$ (0.5 mol%, 3.5 mg). The crude residue was analyzed by ^{1}H NMR (the ratio of **7.18**:**7.19** >20:1) and then purified by flash column chromatography (hexanes/ethyl acetate = 50/1) to afford the product (**7.18**) as a colorless oil (127.3 mg, 82%).

$[\alpha]^{20}_{D:}$ 63.6° (*c* = 6.48, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.42 (d, *J* = 8.4 Hz, 2H), 7.18 (d, *J* = 8.4 Hz, 2H), 7.05 (d, *J* = 8.0 Hz, 2H), 7.00 (d, *J* = 8.0 Hz, 2H), 3.80 (t, *J* = 7.8 Hz, 1H), 3.61 (s, 3H), 3.35 (dd, *J* = 8.4, 13.6 Hz, 1H), 2.96 (dd, *J* = 6.8, 13.6 Hz, 1H), 2.56 (t, 7.6 Hz, 2H), 1.60-1.54 (m, 1H), 1.50-1.44 (m, 2H), 0.92 (d, *J* = 6.4 Hz, 6H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 173.5, 141.2, 137.6, 135.6, 131.7, 129.7, 128.7, 128.4, 121.3, 53.0, 52.1, 40.7, 39.2, 33.3, 27.7, 22.5; IR (neat): 2953, 2868, 1737, 1488, 1434, 1157, 1012, 816; HRMS (FTMS+p-APCI) calcd for $C_{21}H_{26}O_2Br$ $(M+H)^+$ 389.11107 found 389.11104; HPLC (S,S-Whelk, 0% isopropanol in hexane, 0.5 mL/min, 1 mg/mL, 30 min, UV 230 nm) retention times of 14.8 min (major) and 17.0 min (minor), 95% ee.



methyl 2-(4-bromophenyl)-5-methyl-3-(*p*-tolyl)hexanoate (**7.19**-major diasteromer)

Note: The major diasteromer of (**7.19**) was isolated and characterized during the early optimization study with Rh_2(*R*-DPCP)$_4$ catalyst, as follows:



Prepared according to the general procedure for optimization studies on selective C–H functionalization using methyl 2-(4-bromophenyl)-2-diazoacetate (**7.1**) (0.4 mmol, 102 mg, 1.0 equiv), 1-isopentyl-4-methylbenzene (**7.17**) (77.3 mg, 5.0 equiv), Rh_2(*R*-DPCP)$_4$

(1.0 mol%, 4.6 mg) in reflux 2,3-dimethylbutane. The crude residue was analyzed by ^{1}H NMR (the ratio of **7.18**:**7.19** = 1:1.5, dr of product **7.19** is 2.6:1) and then purified by flash column chromatography (hexanes/ethyl acetate = 50/1) to afford the combined products **7.18** and **7.19** as a mixture (114.4 mg, 73% combined yield).

The mixture of these products was partially separable and was then purified three times by column chromatography (hexanes/ethyl acetate = 100/1) to collect clean fractions of the major isomer **7.19** (34.3 mg) for characterization.

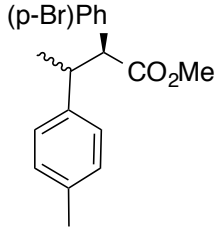
The new stereocenter from the carbenoid site was assigned as (*S*) by analogy with the sterocenter formed with primary C–H insertion; the benzylic stereocenter formed was assigned based on the shielding effects of the toluene methyl group, the chemical shift of the toluene methyl in major isomer is 2.2 ppm while the minor isomer is 2.3 ppm.

Characterization data for major isomer of product **7.19**:

^{1}H NMR (400 MHz, $CDCl_3$): δ 7.23 (d, *J* = 8.4 Hz, 2H), 7.00 (d, *J* = 8.4 Hz, 2H), 6.92 (d, *J* = 8.0 Hz, 2H), 6.81 (d, *J* = 8.0 Hz, 2H), 3.71 (s, 3H), 3.65 (d, *J* = 11.2 Hz, 1H), 3.35-3.28 (m, 1H), 2.22 (s, 3H), 1.76-1.69 (m, 1H), 1.41-1.34 (m, 1H), 1.26-1.20 (m 1H), 0.88 (d, *J* = 6.6 Hz, 3H), 0.80 (d, 6.6 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 173.8, 137.8, 136.5, 135.6, 131.1, 130.3, 128.8, 127.9, 120.8, 58.4, 52.0, 46.9, 43.9, 25.2, 24.1, 20.9, 20.8; IR (neat): 2953, 2868, 1736, 1488, 1266, 1157, 1011, 819; HRMS (APCI) calcd for $C_{21}H_{24}O_2Br$ $(M-H)^+$ 387.09652 found 387.09649.

Products of C–H functionalization of ethyltoluene

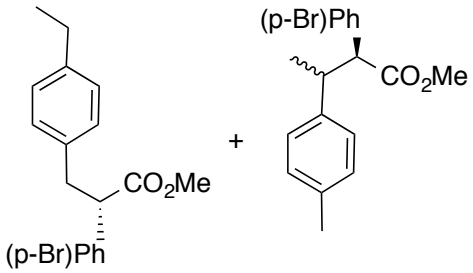
(a) Conditions when Rh_2(*R*-DOSP)$_4$ was used as catalyst.



methyl 2-(4-bromophenyl)-3-(*p*-tolyl)butanoate (**7.22**)

Prepared according to the general procedure for selective C–H functionalization using methyl 2-(4-bromophenyl)-2-diazoacetate (**7.1**) (0.4 mmol, 102 mg, 1.0 equiv), 4-ethyl toluene (**7.20**) (60.7 mg, 1.2 equiv), Rh_2(*R*-DOSP)$_4$ (0.5 mol%, 3.8 mg). The crude residue was analyzed by ^{1}H NMR (the ratio of **7.21**:**7.22** < 20:1, dr of product (**7.22**) is 3.3:1) and then purified by flash column chromatography (hexanes/ethyl acetate = 50/1) to afford the product (**7.22)** in a mixture of diastereomers (103.5 mg, 75% isolated yield). The selectivity trends and spectrum are consistent with previously reported data.[21]

(b) Conditions when Rh_2(*R*-BPCP)$_4$ was used as catalyst.



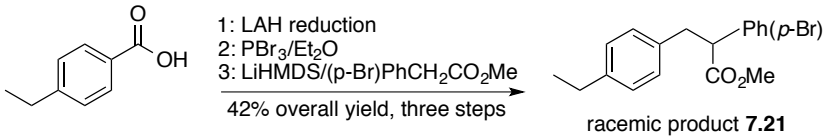
methyl (*S*)-2-(4-bromophenyl)-3-(4-ethylphenyl)propanoate (**7.21**) and methyl 2-(4-bromophenyl)-3-(p-tolyl)butanoate (**7.22**)

Prepared according to the general procedure for selective C–H functionalization using methyl 2-(4-bromophenyl)-2-diazoacetate (**7.1**) (0.4 mmol, 102 mg, 1.0 equiv), 4-ethyl toluene **5** (60.7 mg, 1.2 equiv), Rh_2(*R*-BPCP)$_4$ (0.5 mol%, 3.5 mg). The crude residue was analyzed by ^{1}H NMR (the ratio of **7.21**:**7.22** is 5/1, the dr of product **7.22** is 2.6/1)

[21] Davies, H. M. L.; Jin, Q.; Ren, P.; Kovalevsky, A. Y. *J. Org. Chem.* **2002**, *67*, 4165.

and then purified by flash column chromatography (hexanes/ethyl acetate = 50/1) to afford the combined products (**7.21**) and (**7.22**) in an inseparable mixture (102 mg, 74% combined yield).

In order to test the enantioselectivity of the product (**7.21**), the other method was taken to synthesize the racemic sample of product (**7.21**) due to the difficult separation of these products from the reaction. The racemic sample of (**7.21**) was easily obtained by a general approach starting from commercially available material, as follows:



racemic product **7.21**

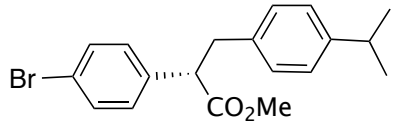
methyl-2-(4-bromophenyl)-3-(4-ethylphenyl)propanoate (R/S-**7.21**-racemic sample)

^{1}H NMR (400 MHz, $CDCl_3$): δ 7.43 (d, *J* = 8.4 Hz, 2H), 7.18 (d, *J* = 8.4 Hz, 2H), 7.07 (d, *J* = 8.2 Hz, 2H), 7.00 (d, *J* = 8.2 Hz, 2H), 3.83 (t, *J* = 8.0 Hz, 1H), 3.62 (s, 3H), 3.36 (dd, *J* = 8.0, 13.6 Hz, 1H), 2.98 (dd, *J* = 6.8, 14.0 Hz, 1H), 2.60 (q, *J* = 7.6 Hz, 2H), 1.21 (t, *J* = 7.6 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 173.5, 142.4, 137.6, 135.7, 131.7, 129.7, 128.8, 127.9, 121.3, 53.1, 52.1, 39.2, 28.4, 15.5; IR (neat, cm^{-1}): 2961, 2871, 1734, 1488, 1154, 1011, 819, 757; HRMS (FTMS+p-NSI) calcd for $C_{18}H_{20}O_2Br$ $(M+H)^+$ 347.06412 found 347.06439.

The enantioselectivity of product (**7.21**) from the Rh_2(*R*-BPCP)$_4$-catalyzed reaction was obtained from HPLC analysis by comparing with the retention times with the racemic sample under the same conditions; product (**7.21**), HPLC (S,S-Whelk, 0% isopropanol in hexane, 0.2 mL/min, 1 mg/mL, 60 min, UV 230 nm) retention times of 39.9 min (major) and 48.3 min (minor), 92% ee.

Products of C–H functionalization of isopropyl toluene

(a) Conditions when Rh_2(*R*-BPCP)$_4$ was used as catalyst.

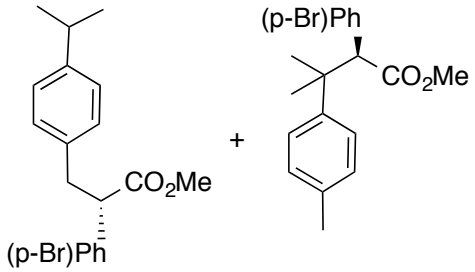


methyl (*S*)-2-(4-bromophenyl)-3-(4-isopropylphenyl)propanoate (**7.24**)

Prepared according to the general procedure for selective C–H functionalization using methyl 2-(4-bromophenyl)-2-diazoacetate (**7.1**) (0.4 mmol, 102 mg, 1.0 equiv), *p*-cymene (**7.23**) (64.3 mg, 1.2 equiv), Rh_2(*R*-BPCP)$_4$ (0.5 mol%, 3.5 mg). The crude residue was analyzed by ^{1}H NMR (the ratio of **7.24** and **7.25** is >20:1) and then purified by flash column chromatography (hexanes/ethyl acetate = 50/1) to afford the product (**7.24**) as a colorless oil (108.6 mg, 75%).

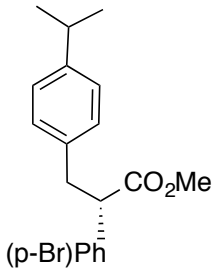
$[\alpha]^{20}_{D:}$ 79.2° (*c* = 1.27, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.45 (d, *J* = 8.0 Hz, 2H), 7.21 (d, *J* = 8.0 Hz, 2H), 7.13 (d, *J* = 8.0 Hz, 2H), 7.05 (d, *J* = 8.0 Hz, 2H), 3.84 (t, *J* = 8.0 Hz, 1H), 3.63 (s, 3H), 3.39 (dd, *J* = 8.4, 13.6 Hz, 1H), 2.99 (dd, *J* = 6.8, 14.0 Hz, 1H), 2.92-2.85 (m, 1H), 1.25 (d, *J* = 6.8 Hz, 6H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 173.4, 146.9, 137.6, 135.8, 131.7, 129.7, 128.7, 126.4, 121.3, 52.9, 52.0, 39.2, 33.6, 23.9; IR (neat, cm^{-1}): 2958, 2867, 1738, 1507, 1488, 1157, 1011, 821; HRMS (FTMS+p-NSI) calcd for $C_{19}H_{22}O_2Br$ $(M+H)^+$ 361.07977 found 361.07983; HPLC (SSWhelk, 0% isopropanol in hexane, 0.5 mL/min, 1 mg/mL, 30 min, UV 230 nm) retention times of 15.6 min (major) and 17.9 min (minor), 97% ee.

(b) Conditions when Rh_2(*R*-DOSP)$_4$ was used as catalyst.



methyl (*S*)-2-(4-bromophenyl)-3-(4-isopropylphenyl)propanoate (**7.24**) and methyl 2-(4-bromophenyl)-3-methyl-3-(*p*-tolyl)butanoate (**7.25**)

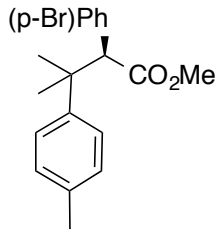
Prepared according to the general procedure for selective C–H functionalization using methyl 2-(4-bromophenyl)-2-diazoacetate (**7.1**) (0.4 mmol, 102 mg, 1.0 equiv), *p*-cymene (**7.23**) (40.4 mg, 1.2 equiv), Rh_2(*R*-DOSP)$_4$ (0.5 mol%, 3.8 mg). The crude residue was analyzed by ^{1}H NMR (the ratio of **7.24**:**7.25** is 1:4) and then purified by flash column chromatography (hexanes/ethyl acetate = 50/1) to afford the combined products in a mixture as a colorless oil (104.0 mg, 72% combined yield). Note: The reaction mixture was partially separable by column chromatography and analytical pure products **417** and **418** were obtained for characterization, as follows:



methyl (*S*)-2-(4-bromophenyl)-3-(4-isopropylphenyl)propanoate (**7.24**)

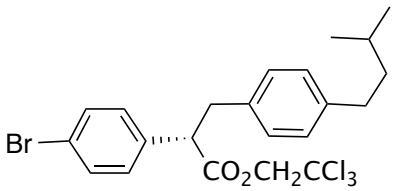
$[\alpha]^{20}_{D:}$ 27.6° (*c* = 0.75, $CHCl_3$); NMR data is consistent with the previously reported results from the Rh_2(*R*-BPCP)$_4$-catalyzed reaction. HPLC (S,S-Whelk, 0% isopropanol in

hexane, 0.5 mL/min, 1 mg/mL, 30 min, UV 230 nm) retention times of 15.6 min (major) and 17.9 min (minor), 73% ee.



methyl 2-(4-bromophenyl)-3-methyl-3-(*p*-tolyl)butanoate (**7.25**)

$[\alpha]^{20}_{D:}$ 33.2° (*c* = 2.11, $CHCl_3$); ^1H NMR (400 MHz, $CDCl_3$): δ 7.32 (d, *J* = 7.6 Hz, 2H), 7.12 (d, *J* = 7.6 Hz, 2H), 7.04 (t, *J* = 9.2 Hz, 1H), 3.80 (s, 1H), 2.29 (s, 3H), 1.44 (s, 3H), 1.30 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 172.6, 143.6, 135.7, 134.5, 131.7, 130.7, 128.6, 126.3, 121.4, 61.7, 51.5, 40.9, 25.8, 25.3, 20.9; IR (neat, cm^{-1}): 2949, 1734, 1488, 1197, 1163, 1139, 1011, 822; HRMS (FTMS+p-NSI) calcd for $C_{19}H_{22}O_2Br$ $(M+H)^+$ 361.07977 found 361.07993; HPLC (ADH, 0% isopropanol in hexane, 0.5 mL/min, 1 mg/mL, 30 min, UV 230 nm) retention times of 9.9 min (minor) and 10.9 min (major), 55% ee.

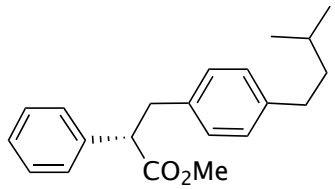


2,2,2-trichloroethyl (*S*)-2-(4-bromophenyl)-3-(4-isopentylphenyl)propanoate (**7.30**)

Prepared according to the general procedure for selective C–H functionalization using 2,2,2-trichloroethyl 2-(4-bromophenyl)-2-diazoacetate (**7.29**) (0.4 mmol, 128.8 mg, 1.0 equiv), 1-isopentyl-4-methylbenzene (**7.17**) (77.3 mg, 1.2 equiv), Rh_2(*R*-BPCP)$_4$ (0.5

mol%, 3.5 mg). The crude residue was analyzed by ^{1}H NMR and purified by flash column chromatography (hexanes/ethyl acetate = 50/1) to afford the product (**7.30**) as a white solid (162 mg, 80%).

White solid, mp: 52-53 °C; $[\alpha]^{20}_{D:}$ 37.2° (*c* = 1.21, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.44 (d, *J* = 8.4 Hz, 2H), 7.23 (d, *J* = 8.4 Hz, 2H), 7.07-7.03 (m, 4H), 4.65 (q, *J* = 12.0, 26.0 Hz, 2H), 3.61 (dd, *J* = 6.8, 8.8 Hz, 1H), 3.41 (t, *J* =8.8, 13.6 Hz, 1H), 3.04 (dd, *J* = 8.8, 13.6 Hz, 1H), 2.54 (t, *J* = 7.8 Hz, 2H), 1.61-1.51 (m, 1H), 1.48-1.43 (m, 2H), 0.92 (d, *J* = 6.4 Hz, 6H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 171.3, 141.5, 136.6, 135.0, 131.7, 129.8, 128.8, 128.4, 121.7, 94.6, 74.1, 52.9, 40.7, 38.9, 33.3, 27.6, 22.5; IR (neat, cm^{-1}): 2954, 2926, 2868, 1754, 1514, 1488, 1137, 1074, 1012, 815, 721; HRMS (FTMS+p-NSI) calcd for $C_{22}H_{24}O_2BrCl_3Na$ 526.99175 found 526.99190; HPLC (SSWhelk, 0% isopropanol in hexane, 0.2 mL/min, 1 mg/mL, 30 min, UV 230 nm) retention times of 68.3 min (major) and 76.2 min (minor), 98% ee.

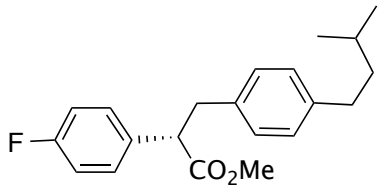


methyl (*S*)-3-(4-isopentylphenyl)-2-phenylpropanoate (**7.28a**)

Prepared according to the general procedure for selective C–H functionalization using methyl 2-diazo-2-phenylacetate (**7.26a**) (0.4 mmol, 70.4 mg, 1.0 equiv), 1-isopentyl-4-methylbenzene (**7.17**) (77.3 mg, 1.2 equiv), Rh_2(*R*-BPCP)$_4$ (0.5 mol%, 3.5 mg). The crude residue was analyzed by ^{1}H NMR and purified by flash column chromatography

(hexanes/ethyl acetate = 50/1) to afford the product (**7.28a**) as a colorless oil (77.0 mg, 62%).

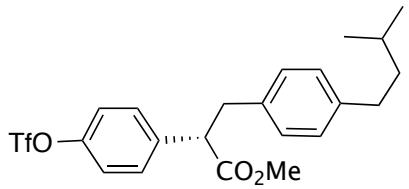
$[\alpha]^{20}_{D:}$ 57.0° (*c* = 3.70, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.33-7.26 (m, 5H), 7.08-7.02 (m, 4H), 7.07-7.03 (m, 4H), 3.85 (dd, *J* = 6.8, 9.2 Hz, 1H), 3.62 (s, 3H), 3.40 (dd, *J* = 9.2, 13.6 Hz, 1H), 3,01 (dd, *J* = 6.4, 13.6 Hz, 1H), 2.57 (t, *J* =8.0 Hz, 2H), 1.61-1.54 (m, 1H), 1.51-1.45 (m, 2H), 0.93 (d, *J* = 6.4 Hz, 6H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 173.9, 141.1, 138.8, 136.1, 128.7, 128.6, 128.3, 127.9, 127.3, 53.7, 51.9, 40.8, 39.4, 33.3, 27.7, 22.5; IR (neat, cm^{-1}): 2952, 2929, 2867, 1737, 1495, 1214, 1156, 698; HRMS (FTMS+p-NSI) calcd for $C_{21}H_{27}O_2$ $(M+H)^+$ 311.20056 found 311.20072; HPLC (ADH, 0% isopropanol in hexane, 0.5 mL/min, 1 mg/mL, 30 min, UV 230 nm) retention times of 11.0 min (major) and 11.9 min (minor), 92% ee.



methyl (*S*)-2-(4-fluorophenyl)-3-(4-isopentylphenyl)propanoate (**7.28b**)

Prepared according to the general procedure for selective C–H functionalization using methyl 2-diazo-2-(4-fluorophenyl)acetate (**7.26b**) (0.4 mmol, 77.6 mg, 1.0 equiv), 1-isopentyl-4-methylbenzene (**7.17**) (77.3 mg, 1.2 equiv), Rh_2(*R*-BPCP)$_4$ (0.5 mol%, 3.5 mg). The crude residue was analyzed by ^{1}H NMR and purified by flash column chromatography (hexanes/ethyl acetate = 50/1) to afford the product (**7.28b**) as a colorless oil (91.8 mg, 70%).

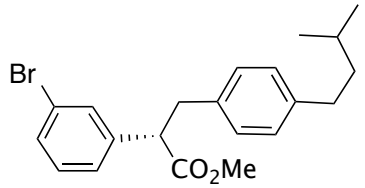
$[\alpha]^{20}_{D:}$ 57.6° (*c* = 3.22, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.26-7.22 (m, 2H), 7.04-6.95 (m, 6H), 3.80 (t, *J* = 8.0 Hz, 1H), 3.59 (s, 3H), 3.34 (dd, *J* = 8.8, 13.6 Hz, 1H), 2.94 (dd, *J* =8.8, 13.6 Hz, 1H), 3.04 (dd, *J* = 8.8, 13.6 Hz, 1H), 2.55 (t, *J* = 7.6 Hz, 2H), 1.58-1.51 (m, 1H), 1.48-1.42 (m, 2H), 0.90 (d, *J* = 6.8 Hz, 6H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 173.8, 163.3, 160.8, 141.2, 135.8, 134.3 (d, *J* = 3.0 Hz), 129.5 (d, *J* = 8.2 Hz), 128.5 (d, *J* = 40.9 Hz), 115.4 (d, *J* = 21.6 Hz), 52.8, 52.0, 40.7, 39.5, 33.3, 27.7, 22.5; IR (neat): 2953, 2868, 1737, 1509, 1436, 1224, 1155, 835; HRMS (FTMS+p-NSI) calcd for $C_{21}H_{26}O_2F$ $(M+H)^+$ 329.19113 found 329.19118; HPLC (S,S-Whelk, 0% isopropanol in hexane, 0.5 mL/min, 1 mg/mL, 60 min, UV 230 nm) retention times of 32.9 min (major) and 37.2 min (minor), 90% ee.



methyl (*S*)-3-(4-isopentylphenyl)-2-(4-(((trifluoromethyl)sulfonyl)oxy)phenyl)propanoate (**7.28c**)

Prepared according to the general procedure for selective C–H functionalization using methyl 2-diazo-2-(4-(((trifluoromethyl)sulfonyl)oxy)phenyl)acetate (**7.26c**) (0.4 mmol, 129.6 mg, 1.0 equiv), 1-isopentyl-4-methylbenzene (**7.17**) (77.3 mg, 1.2 equiv), Rh_2(*R*-BPCP)$_4$ (0.5 mol%, 3.5 mg). The crude residue was analyzed by ^{1}H NMR and purified by flash column chromatography (hexanes/ethyl acetate = 50/1) to afford the product (**7.28c**) as a colorless oil (133.2 mg, 73%).

$[\alpha]^{20}_{D:}$ 44.2° (*c* = 6.63, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.39 (d, *J* = 8.0 Hz, 2H), 7.22 (d, *J* = 8.0 Hz, 2H), 7.06 (d, *J* = 8.0 Hz, 2H), 6.98 (d, *J* = 8.0 Hz, 2H), 3.87 (t, *J* = 8.0 Hz, 1H), 3.64 (s, 3H), 3.38 (dd, *J* = 8.4, 13.6 Hz, 1H), 2.98 (dd, 7.2, 13.6 Hz, 1H), 2.57 (t, *J* = 7.6 Hz, 2H), 1.60-1.52 (m, 1H), 1.50-1.45 (m, 2H), 0.93 (d, *J* = 6.8 Hz, 6H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 173.2, 148.7, 141.4, 139.1, 135.3, 129.9, 128.7, 128.4, 121.4, 52.9, 52.2, 40.7, 39.5, 33.3, 27.6, 22.5; IR (neat): 2956, 2870, 1739, 1501, 1426, 1250, 1213, 1141, 888; HRMS (FTMS+p-NSI) calcd for $C_{22}H_{26}O_5BrF_3S$ $(M+H)^+$ 459.14476 found 459.14527; HPLC (S,S-Whelk, 0% isopropanol in hexane, 0.5 mL/min, 1 mg/mL, 30 min, UV 230 nm) retention times of 12.8 min (major) and 15.8 min (minor), 90% ee.

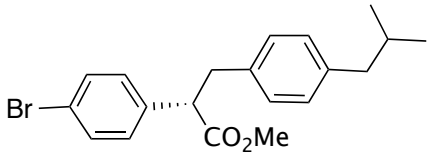


methyl (*S*)-2-(3-bromophenyl)-3-(4-isopentylphenyl)propanoate (**7.28d**)

Prepared according to the general procedure for selective C–H functionalization using methyl 2-(3-bromophenyl)-2-diazoacetate (**7.26d**) (0.4 mmol, 102 mg, 1.0 equiv), 1-isopentyl-4-methylbenzene (**7.17**) (77.3 mg, 1.2 equiv), Rh_2(*R*-BPCP)$_4$ (0.5 mol%, 3.5 mg). The crude residue was analyzed by ^{1}H NMR and purified by flash column chromatography (hexanes/ethyl acetate = 50/1) to afford the product (**7.28d**) as a colorless oil (133.0 mg, 86%).

$[\alpha]^{20}_{D:}$ 46.8° (*c* = 6.09, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.47 (s, 1H), 7.38 (d, *J* = 8.0 Hz, 1H), 7.23 (d, *J* = 8.0 Hz, 1H), 7.16 (t, *J* = 8.0 Hz, 1H), 7.06 (d, *J* = 8.0 Hz, 2H), 7.01 (d, *J* = 8.0 Hz, 2H), 3.75 (t, *J* = 6.8 Hz, 1H), 3.58 (s, 3H), 3.32 (dd, *J* = 8.8, 13.6 Hz,

1H), 2.92 (dd, *J* = 6.4, 13.6 Hz, 1H), 2.52 (t, *J* = 6.4 Hz, 2H), 1.58-1.48 (m, 1H), 1.46-1.40 (m, 2H), 0.92 (d, *J* = 6.4 Hz, 6H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 173.2, 141.2, 140.8, 135.5, 130.9, 130.4, 130.0, 128.7, 128.3, 126.6, 122.6, 53.2, 52.1, 40.7, 39.3, 33.3, 27.6, 22.5; IR (neat): 2952, 2867, 1737, 1592, 1568, 1474, 1157, 691; HRMS (FTMS+p-NSI) calcd for $C_{21}H_{25}O_2BrNa$ $(M+Na)^+$ 411.09311 found 411.09346; HPLC (S,S-Whelk, 0% isopropanol in hexane, 0.5 mL/min, 1 mg/mL, 60 min, UV 230 nm) retention times of 35.8 min (minor) and 41.2 min (major), 77% ee.

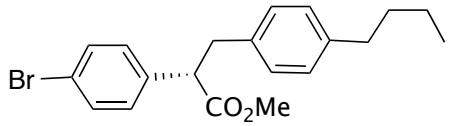


methyl (*S*)-2-(4-bromophenyl)-3-(4-isobutylphenyl)propanoate (**7.28e**)

Prepared according to the general procedure for selective C–H functionalization using methyl 2-(4-bromophenyl)-2-diazoacetate (**7.1**) (0.4 mmol, 102 mg, 1.0 equiv), 1-isobutyl-4-methylbenzene (**7.27a**) (71.0 mg, 1.2 equiv), Rh_2(*R*-BPCP)$_4$ (0.5 mol%, 3.5 mg). The crude residue was analyzed by ^{1}H NMR and purified by flash column chromatography (hexanes/ethyl acetate = 50/1) to afford the product (**7.28e**) as a white foam (131.6 mg, 88%).

Mp = 40-41 °C; $[\alpha]^{20}_{D:}$ 79.2° (*c* = 1.27, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.43 (d, *J* = 8.0 Hz, 2H), 7.03-6.98 (m, 4H), 3.81 (t, *J* = 8.0 Hz, 1H), 3.62 (s, 3H), 3.37 (dd, *J* = 8.0, 16 Hz, 1H), 2.98 (dd, 8.0, 16 Hz, 1H), 2.43 (d, *J* = 8.0 Hz, 2H), 1.88-1.78 (m, 1H), 1.50-1.45 (m, 2H), 0.89 (d, *J* = 6.8 Hz, 6H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 173.5, 139.8, 137.6, 135.7, 131.6, 129.7, 129.1, 128.5, 121.3, 53.1, 52.1, 44.9, 39.3, 30.2, 22.3; IR (neat): 2952, 2924, 2867, 1737, 1488, 1434, 1157, 1012, 875; HRMS (FTMS+p-NSI)

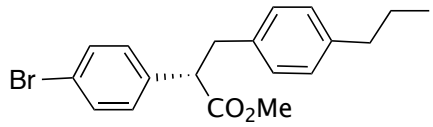
calcd for $C_{20}H_{23}O_2BrNa$ $(M+Na)^+$ 397.07736 found 397.07703; HPLC (S,S-Whelk, 0% isopropanol in hexane, 0.5 mL/min, 1 mg/mL, 30 min, UV 230 nm) retention times of 15.1 min (major) and 17.3 min (minor), 95% ee.



methyl (*S*)-2-(4-bromophenyl)-3-(4-butylphenyl)propanoate (**7.28f**)

Prepared according to the general procedure for selective C–H functionalization using methyl 2-(4-bromophenyl)-2-diazoacetate (**7.1**) (0.4 mmol, 102 mg, 1.0 equiv), 1-butyl-4-methylbenzene (**7.27b**) (71.0 mg, 1.2 equiv), Rh_2(*R*-BPCP)$_4$ (0.5 mol%, 3.5 mg). The crude residue was analyzed by ^{1}H NMR and purified by flash column chromatography (hexanes/ethyl acetate = 50/1) to afford the product (**7.28f**) as a colorless oil (128.0 mg, 86%).

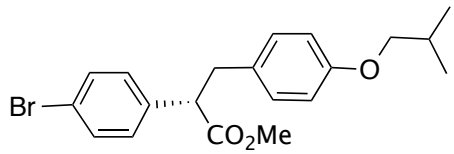
$[\alpha]^{20}_{D:}$ 78.8° (*c* = 6.20, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.45 (d, *J* = 8.0 Hz, 2H), 7.20 (d, *J* = 8.0 Hz, 2H), 7.08 (d, *J* = 8.0 Hz, 2H), 7.03 (d, *J* = 8.0 Hz, 2H), 3.83 (t, *J* = 8.0 Hz, 1H), 3.63 (s, 3H), 3.38 (dd, *J* = 8.0, 13.6 Hz, 1H), 2.99 (dd, *J* = 6.8, 13.6 Hz, 1H), 2.58 (t, *J* = 8.0 Hz, 2H), 0.95 (t, *J* = 6.8 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 173.4, 140.9, 137.6, 135.6, 131.6, 129.7, 128.6, 128.4, 121.2, 53.0, 52.0, 39.2, 35.2, 33.5, 22.3, 13.9; IR (neat): 2953, 2928, 2857, 1736, 1488, 1156, 1011, 819, 757; HRMS (FTMS+p-NSI) calcd for $C_{20}H_{23}O_2BrNa$ 397.07736 found 397.07703; HPLC (SSWhelk, 0% isopropanol in hexane, 0.5 mL/min, 1 mg/mL, 30 min, UV 230 nm) retention times of 15.4 min (major) and 18.0 min (minor), 96% ee.



methyl (*S*)-2-(4-bromophenyl)-3-(4-propylphenyl)propanoate (**7.28g**)

Prepared according to the general procedure for selective C–H functionalization using methyl 2-(4-bromophenyl)-2-diazoacetate (**7.1**) (0.4 mmol, 102 mg, 1.0 equiv), 1-butyl-4-methylbenzene (**7.27c**) (71.0 mg, 1.2 equiv), Rh_2(*R*-BPCP)$_4$ (0.5 mol%, 3.5 mg). The crude residue was analyzed by ^{1}H NMR and purified by flash column chromatography (hexanes/ethyl acetate = 50/1) to afford the product (**7.28g**) as a colorless oil (120.0 mg, 83%).

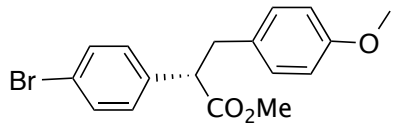
$[\alpha]^{20}_{D:}$ 62.1° (*c* = 5.95, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.42 (d, *J* = 8.0 Hz, 2H), 7.17 (d, *J* = 8.0 Hz, 2H), 7.05 (d, *J* = 8.0 Hz, 2H), 7.00 (d, *J* = 8.0 Hz, 2H), 3.80 (t, *J* = 8.0 Hz, 1H), 3.60 (s, 3H), 3.36 (dd, *J* = 8.0, 13.6 Hz, 1H), 2.97 (dd, *J* = 6.8, 13.6 Hz, 1H), 2.53 (t, *J* = 8.0 Hz, 2H), 1.65-1.56 (m, 1H), 0.92 (t, *J* = 6.8 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 173.5, 140.8, 137.6, 135.6, 131.7, 129.7, 128.6, 128.4, 121.2, 53.0, 52.0, 39.2, 37.6, 24.5, 13.8; IR (neat): 2955, 2928, 2870, 1736, 1488, 1156, 1011, 813, 757; HRMS (FTMS+p-NSI) calcd for $C_{19}H_{22}O_2Br$ $(M+H)^+$ 361.07977 found 361.08010; HPLC (S,S-Whelk, 0% isopropanol in hexane, 0.5 mL/min, 1 mg/mL, 30 min, UV 230 nm) retention times of 15.5 min (major) and 18.2 min (minor), 96% ee.



methyl (*S*)-2-(4-bromophenyl)-3-(4-isobutoxyphenyl)propanoate (**7.28h**)

Prepared according to the general procedure for selective C-H functionalization using methyl 2-(4-bromophenyl)-2-diazoacetate (**7.1**) (0.4 mmol, 102 mg, 1.0 equiv), 1-isobutoxy-4-methylbenzene (**7.27d**) (79.0 mg, 1.2 equiv), Rh_2(*R*-BPCP)$_4$ (0.5 mol%, 3.5 mg). The crude residue was analyzed by ^{1}H NMR and purified by flash column chromatography (hexanes/ethyl acetate = 50/1) to afford the product (**7.28h**) as a colorless oil (132.6 mg, 85%).

$[\alpha]^{20}_{D:}$ 58.5° (*c* = 7.42, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.44 (d, *J* = 8.4 Hz, 2H), 7.18 (d, *J* = 8.4 Hz, 2H), 7.01 (d, *J* = 7.4 Hz, 2H), 6.78 (d, *J* = 7.4 Hz, 2H), 3.79 (t, *J* = 7.6 Hz, 1H), 3.68 (d, *J* = 6.8, 1H), 3.62 (s, 3H), 3.34 (dd, *J* = 8.0, 13.6 Hz, 1H), 2.96 (dd, *J* = 7.6, 14.0 Hz, 1H), 2.11-2.04 (m, 1H), 1.02 (t, *J* = 6.8 Hz, 6H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 173.4, 157.8, 137.5, 131.6, 130.2, 129.7, 129.6, 121.2, 114.3, 74.3, 53.2, 52.0, 38.8, 28.2, 19.2; IR (neat): 2956, 2872, 1736, 1512, 1244, 1157, 1011, 820; HRMS (FTMS+p-NSI) calcd for $C_{20}H_{24}O_3Br$ $(M+H)^+$ 391.09033 found 391.09099; HPLC (S,S-Whelk, 0% isopropanol in hexane, 0.5 mL/min, 1 mg/mL, 40 min, UV 230 nm) retention times of 20.7 min (major) and 25.2 min (minor), 91% ee.

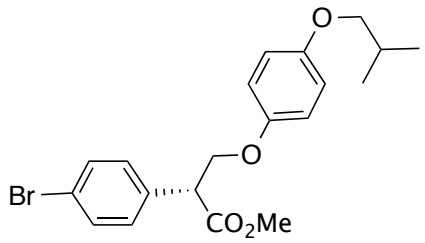


methyl (*S*)-2-(4-bromophenyl)-3-(4-methoxyphenyl)propanoate (**7.28i**)

Prepared according to the general procedure for selective C–H functionalization using methyl 2-(4-bromophenyl)-2-diazoacetate (**7.1**) (0.4 mmol, 102 mg, 1.0 equiv), 1-methoxy-4-methylbenzene (**7.27e**) (58.6 mg, 1.2 equiv), Rh_2(*R*-BPCP)$_4$ (0.5 mol%, 3.5 mg). The crude residue was analyzed by ^{1}H NMR and purified by flash column

chromatography (hexanes/ethyl acetate = 50/1) to afford the product (**7.28i**) as a colorless oil (118.3 mg, 85%). The NMR spectrum is consistent with previously reported data.[22]

$[\alpha]^{20}_{D:}$ 66.6° (*c* = 2.20, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.43 (d, *J* = 8.0 Hz, 2H), 7.16 (d, *J* = 8.0 Hz, 2H), 7.01 (d, *J* = 7.4 Hz, 2H), 6.77 (d, *J* = 7.4 Hz, 2H), 3.79-3.75 (m, 4H), 3.62 (s, 3H), 3.32 (dd, *J* = 8.0, 13.6 Hz, 1H), 2.94 (dd, *J* = 7.2, 13.6 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 173.5, 158.1, 137.5, 131.7, 130.5, 129.8, 129.7, 121.3, 113.7, 55.1, 53.2, 52.1, 38.8; HPLC (ADH, 1 % isopropanol in hexane, 0.5 mL/min, 1 mg/mL, 60 min, UV 230 nm) retention times of 23.5 min (major) and 26.2 min (minor), 90% ee.



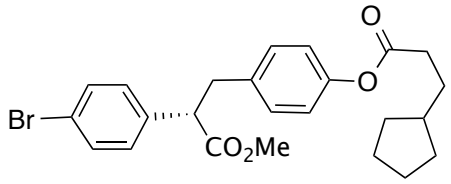
methyl (*R*)-2-(4-bromophenyl)-3-(4-isobutoxyphenoxy)propanoate (**7.28j**)

Prepared according to the general procedure for selective C–H functionalization using methyl 2-(4-bromophenyl)-2-diazoacetate (**7.1**) (0.4 mmol, 102 mg, 1.0 equiv), 1-isobutoxy-4-methoxybenzene (**7.27f**) (86.4 mg, 1.2 equiv), Rh_2(*R*-BPCP)$_4$ (0.5 mol%, 3.5 mg). The crude residue was analyzed by ^{1}H NMR and purified by flash column chromatography (hexanes/ethyl acetate = 50/1) to afford the product (**7.28j**) as a colorless oil (110.4 mg, 68%).

$[\alpha]^{20}_{D:}$ 21.8° (*c* = 1.51, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.46 (d, *J* = 8.4 Hz, 2H), 7.23 (d, *J* = 8.4 Hz, 2H), 6.79 (s, 4H), 4.46 (t, *J* = 8.4 Hz, 1H), 4.08 (dd, *J* = 5.6, 8.8 Hz, 1H), 4.02 (dd, *J* = 5.6, 8.4 Hz, 1H), 3.71 (s, 3H), 3.64 (t, *J* = 6.4 Hz, 2H), 2.08-1.99 (m,

[22] Davies, H. M. L.; Jin, Q. *Tetrahedron: Asymmetry*, **2003**, *14*, 941.

1H), 0.99 (d, J = 6.8 Hz, 6H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 171.9, 153.9, 152.3, 134.4, 131.9, 129.9, 121.9, 115.9, 115.3, 75.0, 69.9, 52.3, 50.9, 28.3, 19.2; IR (neat): 2955, 2872, 1740, 1507, 1489, 1228, 1166, 1011; HRMS (FTMS+p-NSI) calcd for $C_{20}H_{24}O_4Br$ $(M+H)^+$ 407.08525 found 407.08525; HPLC (S,S-Whelk, 0% isopropanol in hexane, 0.5 mL/min, 1 mg/mL, 80 min, UV 230 nm) retention times of 48.5 min (minor) and 57.6 min (major), 90% ee.

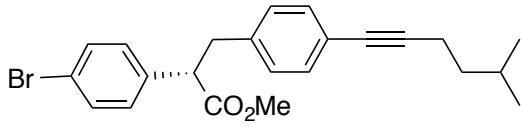


methyl (*S*)-2-(4-bromophenyl)-3-(4-((3-cyclopentylpropanoyl)oxy)phenyl)propanoate (**7.28k**)

Prepared according to the general procedure for selective C–H functionalization using methyl 2-(4-bromophenyl)-2-diazoacetate (**7.1**) (0.4 mmol, 102 mg, 1.0 equiv), *p*-tolyl 3-cyclopentylpropanoate (**7.27g**) (111.4 mg, 1.2 equiv), Rh_2(*R*-BPCP)$_4$ (0.5 mol%, 3.5 mg). The crude residue was analyzed by ^{1}H NMR and purified by flash column chromatography (hexanes/ethyl acetate = 50/1) to afford the product (**7.28k**) as a colorless oil (106.0 mg, 58%).

$[\alpha]^{20}_{D:}$ 61.6° (*c* = 1.89, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.43 (d, J = 8.0 Hz, 2H), 7.16 (d, J = 8.0 Hz, 2H), 7.09 (d, J = 8.0 Hz, 2H), 6.95 (d, J = 8.0 Hz, 2H), 3.79 (t, J = 8.0 Hz, 1H), 3.62 (s, 3H), 3.38 (dd, J = 8.4, 13.6 Hz, 1H), 2.98 (dd, J = 7.2, 13.6 Hz, 1H), 2.56 (t, J = 7.6 Hz, 2H), 1.86-1.74 (m, 5H), 1.67-1.54 (m, 4H), 1.18-1.30 (m, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 173.2, 172.4, 149.3, 137.3, 135.9, 131.8, 131.7, 129.8, 129.7,

121.4, 52.9, 52.1, 39.6, 38.9, 33.7, 32.4, 31.0, 25.1; IR (neat): 2949, 2865, 1756, 1738, 1507, 1488, 1262, 1166, 1125, 1011; HRMS (FTMS+p-NSI) calcd for $C_{24}H_{27}O_4BrNa$ $(M+Na)^+$ 481.09849 found 481.09817; HPLC (ODH, 0.2 % isopropanol in hexane, 0.5 mL/min, 1 mg/mL, 40 min, UV 230 nm) retention times of 17.8 min (major) and 26.0 min (minor), 95% ee.

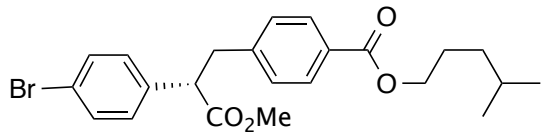


methyl (*S*)-2-(4-bromophenyl)-3-(4-(5-methylhex-1-yn-1-yl)phenyl)propanoate (**7.28l**)

Prepared according to the general procedure for selective C–H functionalization using methyl 2-(4-bromophenyl)-2-diazoacetate (**7.1**) (0.4 mmol, 102 mg, 1.0 equiv), 1-methyl-4-(5-methylhex-1-yn-1-yl)benzene (**7.27h**) (89.3 mg, 1.2 equiv), Rh_2(*R*-BPCP)$_4$ (0.5 mol%, 3.5 mg). The crude residue was analyzed by ^{1}H NMR and purified by flash column chromatography (hexanes/ethyl acetate = 50/1) to afford the product **7.28l** as a light yellow oil (108.7 mg, 66%).

$[\alpha]^{20}_{D:}$ 95.9° (*c* = 3.78, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.39 (d, *J* = 8.4 Hz, 2H), 7.24 (d, *J* = 8.4 Hz, 2H), 7.12 (d, *J* = 8.4 Hz, 2H), 6.97 (d, *J* = 8.4 Hz, 2H), 3.75 (t, *J* = 8.0 Hz, 1H), 3.59 (s, 3H), 3.33 (dd, *J* = 8.0, 13.6 Hz, 1H), 2.94 (dd, *J* = 7.2, 13.6 Hz, 1H), 2.38 (t, *J* = 7.6 Hz, 2H), 1.77-1.69 (m, 1H), 1.50-1.44 (m, 2H), 0.91 (d, *J* = xx Hz, 6H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 173.2, 137.9, 137.2, 131.7, 131.5, 129.7, 128.8, 122.2, 121.4, 90.4, 80.1, 52.8, 52.1, 39.5, 37.6, 27.2, 22.2, 17.4; IR (neat): 2952, 2929, 2868, 1736, 1156, 1011, 820, 757; HRMS (FTMS+p-NSI) calcd for $C_{23}H_{26}O_2Br$ $(M+H)^+$ 413.11107 found 413.1113; HPLC (ADH, 0% isopropanol in hexane, 0.5 mL/min, 1

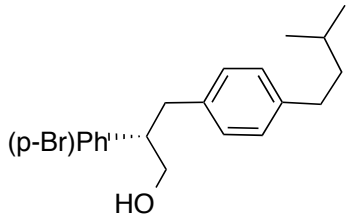
mg/mL, 30 min, UV 230 nm) retention times of 13.0 min (major) and 14.4 min (minor), 94% ee.



4-methylpentyl (*S*)-4-(2-(4-bromophenyl)-3-methoxy-3-oxopropyl)benzoate (Table 2, **7.28m**)

Prepared according to the general procedure for selective C–H functionalization using methyl 2-(4-bromophenyl)-2-diazoacetate (**7.1**) (0.4 mmol, 102 mg, 1.0 equiv.), isopentyl 4-methylbenzoate (**7.27i**) (105.6 mg, 1.2 equiv), Rh_2(*R*-BPCP)$_4$ (0.5 mol%, 3.5 mg). The crude residue was analyzed by ^{1}H NMR and purified by flash column chromatography (hexanes/ethyl acetate = 50/1) to afford the product (**7.28m**) as a colorless oil (67.8 mg, 38%).

$[\alpha]^{20}_{D:}$ 74.8° (*c* = 0.82, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.92 (d, *J* = 8.4 Hz, 2H), 7.43 (d, *J* = 8.4 Hz, 2H), 7.17-7.14 (m, 4H), 4.28 (t, *J* = 7.2 Hz, 2H), 3.82 (t, *J* = 7.6 Hz, 1H), 3.68 (s, 3H), 3.43 (dd, *J* = 8.4, 13.6 Hz, 1H), 3.05 (dd, *J* = 7.2, 13.6 Hz, 1H), 1.79-1.72 (m, 2H), 1.64-1.57 (m, 1H), 1.34-1.28 (m, 2H), 0.92 (d, *J* = 6.4 Hz, 6H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 173.0, 166.4, 143.7, 136.9, 131.8, 129.6, 128.9, 128.8, 121.5, 65.3, 52.5, 52.2, 39.5, 35.0, 27.7, 26.6, 22.5; IR (neat): 2953, 2869, 1736, 1714, 1611, 1272, 1156, 1099, 1011, 756, 704; HRMS (FTMS+p-NSI) calcd for $C_{23}H_{28}O_4Br$ $(M+H)^+$ 447.11655 found 447.11710; HPLC (ODH, 0.3% isopropanol in hexane, 0.5 mL/min, 1 mg/mL, 30 min, UV 230 nm) retention times of 12.7 min (major) and 14.6 min (minor), 94% ee.

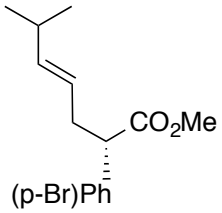


(*S*)-2-(4-bromophenyl)-3-(4-isopentylphenyl)propan-1-ol (**7.31**)

^{1}H NMR (400 MHz, $CDCl_3$): δ 7.44 (d, *J* = 8.4 Hz, 2H), 7.08 (t, *J* = 8.4 Hz, 2H), 7.00 (d, *J* = 8.4 Hz, 2H), 3.80-3.72 (m, 2H), 3.08-2.96 (m, 2H), 2.87-2.82 (m, 1H), 2.57 (t, *J* = 8.0 Hz, 2H), 1.62-1.55 (m, 1H), 1.52-1.47 (m, 2H), 0.95 (d, *J* = 6.4 Hz, 6H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 141.1, 140.8, 136.5, 131.5, 129.8, 128.8, 128.2, 120.4, 66.1, 49.6, 40.7, 38.1, 33.3, 27.6, 22.5; IR (neat): 3331, 2951, 2925, 2867, 1513, 1487, 1072, 1009, 819; HRMS (FTMS+p-NSI) calcd for $C_{20}H_{25}OBrNa$ 383.09810 found 383.09735.

Products of C-H functionalization of *E*)-4-methylpent-2-ene

(a) Conditions when Rh_2(*R*-BPCP)$_4$ was used as catalyst.

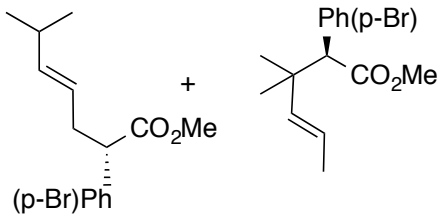


methyl (*S*,*E*)-2-(4-bromophenyl)-6-methylhept-4-enoate (**7.33**)

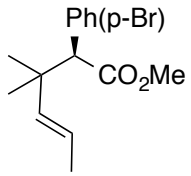
Prepared according to the general procedure for selective C–H functionalization using methyl 2-(4-bromophenyl)-2-diazoacetate (**7.1**) (0.4 mmol, 102 mg, 1.0 equiv), (*E*)-4-methylpent-2-ene (**7.32**) (40.4 mg, 1.2 equiv), Rh_2(*R*-BPCP)$_4$ (0.5 mol%, 3.5 mg). The crude residue was analyzed by ^{1}H NMR (the ratio of **7.33** and **7.34** is 17:1) and then purified by flash column chromatography (hexanes/ethyl acetate = 80/1) to afford the product **7.33** as a colorless oil (74.4 mg, 60%).

$[\alpha]^{20}_{D:}$ 35.8° (*c* = 2.74, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.44 (d, *J* = 8.4 Hz, 2H), 7.18 (d, *J* = 8.4 Hz, 2H), 5.45-5.39 (m, 1H), 5.27-5.20 (m, 1H), 3.66 (s, 3H), 3.55 (t, *J* = 8.0 Hz, 1H), 2.74-2.67 (m, 1H), 2.44-2.36 (m, 1H), 2.21-2.16 (m, 1H), 0.91 (q, *J* = 4.4 Hz, 6H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 173.6, 140.9, 137.7, 131.6, 129.7, 122.8, 121.1, 51.9, 51.4, 36.5, 30.9, 22.4; IR (neat): 2955, 2868, 1738, 1489, 1464, 1160, 1011, 970, 820; HRMS (FTMS+p-NSI) calcd for $C_{15}H_{20}O_2Br$ $(M+H)^+$ 311.06412 found 311.06408; HPLC (S,S-Whelk, 0% isopropanol in hexane, 0.5 mL/min, 1 mg/mL, 30 min, UV 230 nm) retention times of 14.5 min (major) and 16.1 min (minor), 94% ee.

(b) Conditions when Rh_2(*R*-DOSP)$_4$ was used as catalyst.



Prepared according to the general procedure for selective C–H functionalization using methyl 2-(4-bromophenyl)-2-diazoacetate (**7.1**) (0.4 mmol, 102 mg, 1.0 equiv), (*E*)-4-methylpent-2-ene (**7.32**) (40.4 mg, 1.2 equiv), Rh_2(*R*-DOSP)$_4$ (0.5 mol%, 3.8 mg). The crude residue was analyzed by ^{1}H NMR (the ratio of **7.33** and **7.34** is 1/7) and then purified by flash column chromatography (hexanes/ethyl acetate = 50/1) to afford the combined products in a mixture as a colorless oil (100.2 mg, 81% combined yield). Note: The reaction mixture was partially separable by column chromatography (hexanes/ethyl acetate = 100/1), providing analytical pure product (**7.34**) for characterization, as follows:

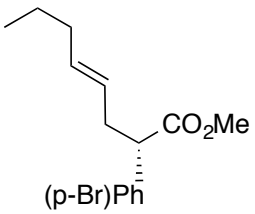


methyl (*E*)-2-(4-bromophenyl)-3,3-dimethylhex-4-enoate (**7.34**)

$[\alpha]^{20}_{D:}$ 6.68° (*c* = 3.36, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.41 (d, *J* = 8.0 Hz, 2H), 7.24 (d, *J* = 8.0 Hz, 2H), 5.57 (d, *J* = 16.0 Hz, 1H), 5.26 (dq, *J* = 6.4, 19.2 Hz, 1H), 3.61 (s, 3H), 3.42 (s, 3H), 1.63 (dd, *J* = 1.6, 6.4 Hz, 3H), 1.01 (d, *J* = 5.6 Hz, 6H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 172.8, 137.4, 134.8, 131.7, 130.7, 123.3, 121.3, 60.8, 51.4, 39.3, 26.2, 24.5, 18.1; IR (neat): 2963, 1733, 1488, 1139, 1011, 973, 832; HRMS (FTMS+p-NSI) calcd for $C_{15}H_{20}O_2Br$ $(M+H)^+$ 311.06412 found 311.06411; HPLC (AHD, 0% isopropanol in hexane, 0.5 mL/min, 1 mg/mL, 30 min, UV 230 nm) retention times of 7.8 min (major) and 8.8 min (minor), 48% ee.

Products of C–H functionalization of (*E*)-2-hexene

(a) Conditions when Rh_2(*R*-BPCP)$_4$ was used as catalyst.



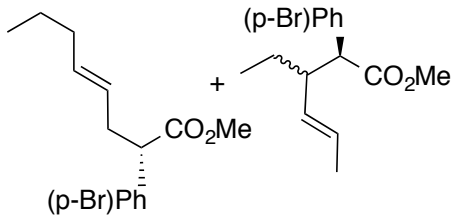
methyl (*S*,*E*)-2-(4-bromophenyl)oct-4-enoate (**7.36**)

Prepared according to the general procedure for selective C–H functionalization using methyl 2-(4-bromophenyl)-2-diazoacetate (**7.1**) (0.4 mmol, 102 mg, 1.0 equiv), (*E*)-hex-2-ene (**7.35**) (40.4 mg, 1.2 equiv), Rh_2(*R*-BPCP)$_4$ (0.5 mol%, 3.5 mg). The crude residue was analyzed by ^{1}H NMR (the ratio of **7.36** and **7.37** is 8:1, the dr of product **7.37** is 1.2:1) and then purified by flash column chromatography (hexanes/ethyl acetate = 50/1)

to afford the combined products in a mixture as a colorless oil (99.2 mg, 80% combined yield). Note: The obtained products mixture was only partially separable after four times of careful column chromatography (hexanes/ethyl acetate = 100/1), providing the analytically pure product **7.37** for characterization, as follows.

$[\alpha]^{20}_{D:}$ 38.3° (*c* = 2.72, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.42 (d, *J* = 8.4 Hz, 2H), 7.16 (d, *J* = 8.4 Hz, 2H), 5.47-5.39 (m, 1H), 5.29-5.21 (m, 1H), 3.63 (s, 3H), 3.54 (t, *J* = 7.6 Hz, 1H), 2.74-2.67 (m, 1H), 2.44-2.36 (m, 1H), 1.92-1.86 (m, 2H), 1.31-1.24 (m, 2H), 0.80 (t, *J* = 7.2 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 173.6, 137.6, 133.5, 131.6, 129.7, 126.1, 121.1, 52.0, 51.4, 36.5, 34.5, 22.4, 13.4; IR (neat): 2955, 2928, 28672 1737, 1488, 1435, 1160, 1011, 969, 821, 757; HRMS (FTMS+p-NSI) calcd for $C_{15}H_{29}O_2BrNa$ $(M+Na)^+$ 333.04606 found 333.04603; HPLC (ADH, 0% isopropanol in hexane, 0.25 mL/min, 1 mg/mL, 80 min, UV 230 nm) retention times of 41.5 min (major) and 55.8 min (minor), 95% ee.

(b) Conditions when Rh_2(*R*-DOSP)$_4$ was used as catalyst.

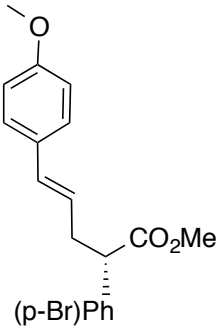


Prepared according to the general procedure for selective C–H functionalization using methyl 2-(4-bromophenyl)-2-diazoacetate (**7.1**) (0.4 mmol, 102 mg, 1.0 equiv), (*E*)-hex-2-ene (**7.35**) (40.4 mg, 1.2 equiv), Rh_2(*R*-DOSP)$_4$ (0.5 mol%, 3.8 mg). The crude residue was analyzed by ^{1}H NMR (the ratio of **7.36** and **7.37** is 1:9, the dr of product **7.37** is 1.8:1) and then purified by flash column chromatography (hexanes/ethyl acetate = 50/1) to afford the combined products in a mixture as a colorless oil (92.4 mg, 75% combined

isolated yield). Note: since the product (**7.37**) dominates in the reaction mixture, isolation pure product (**7.36)** failed. The diasteromer of (**7.37)** was inseparable under column chromatography (hexanes/ethyl acetate = 100/1), and further separation and characterization of product (**7.37)** was not done at this stage.

Products of C–H functionalization of *trans*-anethole

(a) Conditions when Rh_2(*R*-BPCP)$_4$ was used as catalyst.



methyl (*S*,*E*)-2-(4-bromophenyl)-4-(4-methoxyphenyl)but-3-enoate (**7.6**)

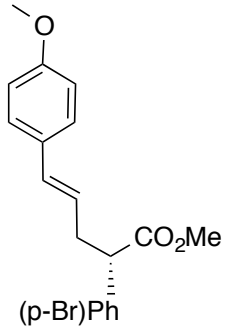
Prepared according to the general procedure for selective C–H functionalization using methyl 2-(4-bromophenyl)-2-diazoacetate (**7.1**) (0.4 mmol, 102 mg, 1.0 equiv), *trans*-anethole (**7.5**) (105.6 mg, 1.2 equiv), Rh_2(*R*-BPCP)$_4$ (0.5 mol%, 3.5 mg). The crude residue was analyzed by ^{1}H NMR (the ratio of **7.6** and **7.7** is 16:1) and then purified by flash column chromatography (hexanes/ethyl acetate = 50/1) to afford product (**7.6**) as a white solid (127.2 mg, 85%). The NMR spectrum is consistent with previously reported data.[23]

$[\alpha]^{20}_{D:}$ 70.2° (*c* = 3.64, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.47 (d, *J* = 8.4 Hz, 2H), 7.25-7.22 (m, 4H), 6.83 (d, *J* = 8.4 Hz, 2H), 6.38 (d, *J* = 15.6 Hz, 1H), 5.98-5.89 (m, 1H), 3.80 (s, 3H), 3.69-3.65 (m, 4H), 2.98-2.90 (m, 1H), 2.67-2.59 (m, 1H); ^{13}C NMR (100

[23] Davies, H. M. L.; Coleman, M. G.; Ventura, D. L. *Org. Lett.* **2007**, *9*, 4971.

MHz, $CDCl_3$) δ 173.4, 158.9, 137.5, 131.9, 131.7, 129.9, 129.7, 127.2, 124.0, 121.3, 113.9, 55.2, 52.1, 51.3, 36.8; IR (neat): 2951, 2836, 1735, 1607, 1510, 1488, 1436, 1247, 1174, 1159, 1017, 1011, 967; HRMS (FTMS+p-NSI) calcd for $C_{19}H_{20}O_3Br$ $(M+H)^+$ 375.05903 found 375.05916; HPLC (ODH, 0.1 % isopropanol in hexane, 0.5 mL/min, 1 mg/mL, 60 min, UV 230 nm) retention times of 22.3 min (minor) and 24.4 min (major), 88% ee.

(b) Conditions when Rh_2(*R*-DOSP)$_4$ was used as catalyst.



methyl (*S*,*E*)-2-(4-bromophenyl)-4-(4-methoxyphenyl)but-3-enoate (**7.6**)

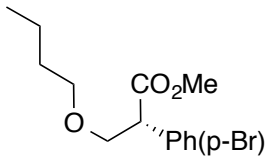
Prepared according to the general procedure for selective C–H functionalization using methyl 2-(4-bromophenyl)-2-diazoacetate (**7.1**) (0.4 mmol, 102 mg, 1.0 equiv), *trans*-anethole (**7.5**) (105.6 mg, 1.2 equiv), Rh_2(*R*-DOSP)$_4$ (0.5 mol%, 3.8 mg). The crude residue was analyzed by ^{1}H NMR (the ratio of **7.6** and **7.7** is 5:1) and then purified by flash column chromatography (hexanes/ethyl acetate = 50/1) to afford the combined product in a mixture (113.2 mg, 76% combined yield). The reaction mixture was then purified by flash chromatography (hexanes/ethyl acetate = 80/1), providing analytically pure product (**7.6**) for characterization, as follows:

$[\alpha]^{20}_{D:}$ 47.3° (*c* = 1.0, $CHCl_3$); NMR data is consistent with the result from Rh_2(*R*-BPCP)$_4$-catalyzed reaction reported here; HPLC (ODH, 0.1 % isopropanol in hexane, 0.5

mL/min, 1 mg/mL, 60 min, UV 230 nm) retention times of 22.2 min (minor) and 24.4 min (major), 76% ee.

Products of C–H functionalization of 1-methoxybutane

(a) Conditions when Rh_2(*R*-BPCP)$_4$ was used as catalyst.

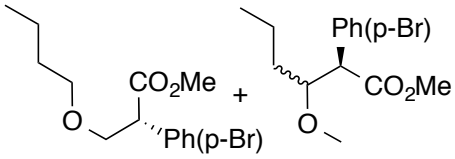


Methyl (*S*)-2-(4-bromophenyl)-2-butoxyacetate (**7.39**)

Prepared according to the general procedure for selective C–H functionalization using methyl 2-(4-bromophenyl)-2-diazoacetate (**7.1**) (0.4 mmol, 102 mg, 1.0 equiv), (1-methoxybutane (**7.38**) (42.3 mg, 1.2 equiv), Rh_2(*R*-BPCP)$_4$ (0.5 mol%, 3.5 mg). The crude residue was analyzed by ^{1}H NMR (the ratio of **7.39** and **7.40** is >20:1) and then purified by flash column chromatography (hexanes/ethyl acetate = 50/1) to afford the product (**7.39**) as a colorless oil (108.0 mg, 86%).

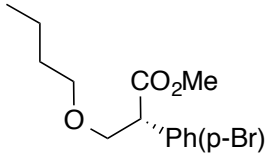
$[\alpha]^{20}_{D:}$ 18.5° (*c* = 1.29, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.46 (d, *J* = 8.0 Hz, 2H), 7.21 (d, *J* = 8.0 Hz, 2H), 3.96 (t, *J* = 8.0 Hz, 1H), 3.85 (dd, *J* = 5.2, 8.8 Hz, 1H), 3.70 (s, 3H), 3.62 (dd, *J* = 5.2, 8.8 Hz, 1H), 3.45 (t, *J* = 6.8 Hz, 2H), 1.56-1.49 (m, 2H), 1.37-1.27 (m, 2H), 0.90 (t, *J* = 8.0 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 172.5, 134.9, 131.7, 129.9, 121.6, 72.0, 71.2, 52.2, 51.4, 31.5, 19.2, 13.8; IR (neat): 2956, 2869, 1739, 1489, 1459, 1202, 1165, 1114, 1074, 1012, 821, 758; HRMS (FTMS+p-NSI) calcd for $C_{14}H_{20}O_3Br$ $(M+H)^+$ 315.05903 found 315.05921; HPLC (ADH, 0% isopropanol in hexane, 0.25 mL/min, 1 mg/mL, 60 min, UV 230 nm) retention times of 27.8 min (minor) and 34.3 min (major), 64% ee.

(b) Conditions when Rh_2(*R*-DOSP)$_4$ was used as catalyst.



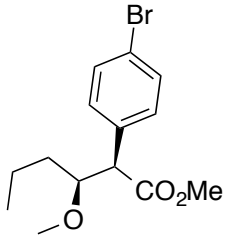
methyl (*S*)-2-(4-bromophenyl)-2-butoxyacetate (**7.39**) and methyl (2*R*)-2-(4-bromophenyl)-3-methoxyhexanoate (**7.40**)

Prepared according to the general procedure for selective C–H functionalization using methyl 2-(4-bromophenyl)-2-diazoacetate (**7.1**) (0.4 mmol, 102 mg, 1.0 equiv), (1-methoxybutane (**7.38**) (42.3 mg, 1.2 equiv), Rh_2(*R*-DOSP)$_4$ (0.5 mol%, 3.8 mg). The crude residue was analyzed by ^{1}H NMR (the ratio of **7.39** and **7.40** is 3:2, the dr of product **7.40** is 1.3/1) and then purified by flash column chromatography (hexanes/ethyl acetate = 50/1) to afford the combined products in a mixture as a colorless oil (96.7 mg, 77% combined yield). Note: the obtained product mixture was then carefully purified by flash column chromatography (hexanes/ethyl acetate = 100/1, five times purification) to get partially separation between these products.



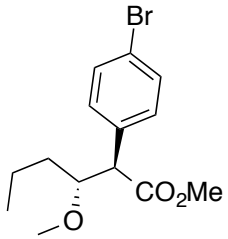
methyl (*S*)-2-(4-bromophenyl)-2-butoxyacetate (**7.39**)

HPLC (ADH, 0% isopropanol in hexane, 0.25 mL/min, 1 mg/mL, 60 min, UV 230 nm) retention times of 27.8 min (minor) and 34.3 min (major), 61% ee. The NMR spectrum is consistent with previously reported data in this chapter.



methyl (2*R*,3*S*)-2-(4-bromophenyl)-3-methoxyhexanoate (**7.40**-major isomer)

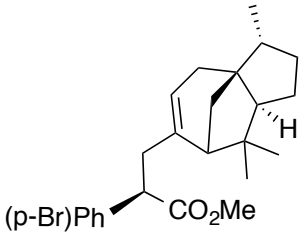
^{1}H NMR (400 MHz, $CDCl_3$): δ 7.42 (d, *J* = 8.0 Hz, 2H), 7.25 (d, *J* = 8.0 Hz, 2H), 3.77-3.72 (m, 1H), 3.66 (s, 3H), 3.61 (d, *J* = 7.6 Hz, 1H), 3.12 (s, 3H), 1.47-1.33 (m, 4H), 0.89 (t, *J* = 7.2 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 172.5, 135.2, 131.4, 130.9, 121.4, 82.3, 58.7, 55.8, 52.1, 35.0, 18.5, 14.1; IR (neat): 2956, 2870, 1737, 1488, 1142, 1092, 1011; HRMS (FTMS+p-NSI) calcd for $C_{14}H_{20}O_3Br$ $(M+H)^+$ 315.05903 found 315.05923.



methyl (2*R*,3*R*)-2-(4-bromophenyl)-3-methoxyhexanoate (**7.40**-minor isomer)

^{1}H NMR (400 MHz, $CDCl_3$): δ 7.45 (d, *J* = 8.0 Hz, 2H), 7.23 (d, *J* = 8.0 Hz, 2H), 3.86-3.81 (m, 1H), 3.69 (s, 3H), 3.62 (d, *J* = 10.0 Hz, 1H), 3.42 (s, 3H), 1.38-1.11 (m, 4H), 0.81 (t, *J* = 7.2 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 173.1, 134.9, 131.8, 130.3, 121.7, 82.2, 58.3, 56.1, 52.1, 32.7, 17.3, 14.2; IR (neat): 2956, 2873, 1737, 1488, 1163, 1090, 1011; HRMS (FTMS+p-NSI) calcd for $C_{14}H_{20}O_3Br$ $(M+H)^+$ 315.05903 found 315.05902.

Note: the new stereocenter from carbenoid site was assigned by analogy with the stereocenter formed in the primary C–H insertion product. The stereocenter of methoxy group was assigned based on the shielding effects of methoxy group. In the major isomer, the chemical shift of methoxy is 3.1 ppm. In the minor isomer, the chemical shift of methoxy group is 3.4 ppm.



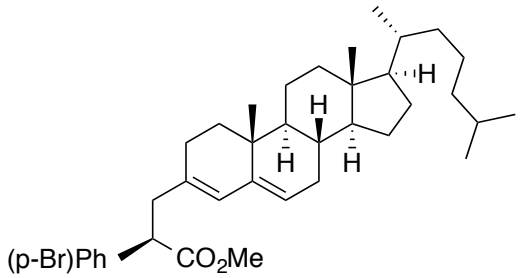
methyl (2*R*)-2-(4-bromophenyl)-3-((3*R*,3a*S*,8a*S*)-3,8,8-trimethyl-2,3,4,7,8,8a-hexahydro-1H-3a,7-methanoazulen-6-yl)propanoate (**7.42**)

Prepared according to the general procedure for selective C–H functionalization using methyl 2-(4-bromophenyl)-2-diazoacetate (**7.1**) (0.4 mmol, 102 mg, 1.0 equiv), (-)-α-cedrene (**7.41**) (98.0 mg, 1.2 equiv), Rh_2(*S*-BPCP)$_4$ (0.5 mol%, 3.5 mg). The crude residue was analyzed by ^{1}H NMR (clean spectrum, no other regioisomers were detected) and purified by flash column chromatography (hexanes/ethyl acetate = 50/1) to afford the product (**7.42**) as a white solid (152.0 mg, 88%).

Mp = 85-86 °C; $[\alpha]^{20}_{D:}$ -13.4° (*c* = 1.03, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.41 (d, *J* = 8.4 Hz, 2H), 7.22 (d, *J* = 8.4 Hz, 2H), 5.31 (br, 1H), 3.70 (dd, *J* = 4.4, 10.4 Hz, 1H), 3.61 (s, 3H), 2.81 (dd, *J* = 11.2, 13.6 Hz, 1H), 2.20-2.12 (m, 2H), 1.86-1.53 (m, 7H), 1.39-1.24 (m, 3H), 0.99 (s, 3H), 0.92 (s, 3H), 0.82 (d, *J* = 7.2 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 173.6, 141.1, 138.1, 131.6, 129.6, 121.2, 121.1, 58.8, 53.9, 53.2, 51.8, 49.9, 48.4, 42.0, 41.3, 40.6, 38.8, 36.0, 27.5, 25.6, 24.7, 15.4; IR (neat): 2948, 2869,

2827, 1739, 1488, 1157, 1012, 823, 756; HRMS (FTMS+p-NSI) calcd for $C_{24}H_{32}O_2Br$ $(M+H)^+$ 431.15802 found 431.15801.

(a) Conditions when Rh_2(*S*-BPCP)$_4$ was used as catalyst.



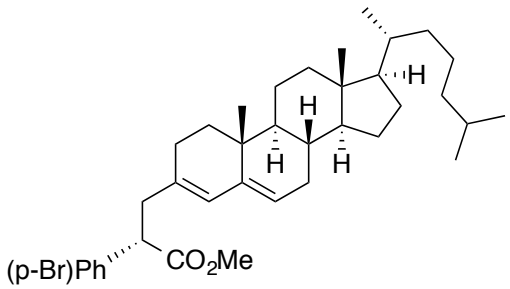
methyl (*R*)-2-(4-bromophenyl)-3-((8*S*,9*S*,10*R*,13*R*,14*S*,17*R*)-10,13-dimethyl-17-((*R*)-6-methylheptan-2-yl)-2,7,8,9,10,11,12,13,14,15,16,17-dodecahydro-1H-cyclopenta[a]phenanthren-3-yl)propanoate (**7.44**-matched diastereomer)

Prepared according to the general procedure for selective C–H functionalization using methyl 2-(4-bromophenyl)-2-diazoacetate (**7.1**) (0.4 mmol, 102 mg, 1.0 equiv), steroid (**7.43**) (183.5 mg, 1.2 equiv), Rh_2(*S*-BPCP)$_4$ (0.5 mol%, 3.5 mg). The crude residue was analyzed by ^{1}H NMR (clean spectrum and no other regioisomers were detected) and purified by flash column chromatography (hexanes/ethyl acetate = 50/1) to afford the product **7.44** as a white solid (233.6 mg, 96%). Note: the absolute configuration of the new stereogenic center generated in the matched reactions was tentatively assigned as (*R*) by analogy.

Mp = 98-100 °C; $[\alpha]^{20}_{D:}$ -152.9° (*c* = 2.35, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.42 (d, *J* = 8.4 Hz, 2H), 7.19 (d, *J* = 8.4 Hz, 2H), 5.67 (s, 1H), 5.29 (s, 1H), 3.77 (t, *J* = 8.0 Hz, 1H), 3.65 (s, 3H), 2.77 (dd, *J* = 8.0, 14.4 Hz, 1H), 2.48 (dd, *J* = 8.4, 14.4 Hz, 1H), 2.16-1.75 (m, 7H), 1.67-1.49 (m, 5H), 1.39-1.25 (m, 6H), 1.21-0.99 (m, 10H), 0.92 (d, *J* = 6.4 Hz, 3H), 0.88 (d, *J* = 2.0, 3H), 0.86 (d, *J* = 2.0, 3H), 0.73 (s, 3H), 0.69 (s, 3H); ^{13}C

NMR (100 MHz, $CDCl_3$) δ 173.7, 141.3, 137.5, 132.4, 131.5, 129.7, 126.8, 122.5, 121.2, 56.8, 56.1, 52.1, 49.5, 48.2, 42.4, 40.9, 39.7, 39.5, 36.1, 35.8, 34.7, 33.9, 31.7, 28.2, 27.9, 26.1, 24.1, 23.8, 22.8, 22.5, 21.0, 18.7, 18.6, 11.9; IR (neat): 2934, 2867, 1739, 1488, 1435, 1159, 1074, 1012, 824, 757; HRMS (FTMS+p-NSI) calcd for $C_{37}H_{54}O_2Br$ $(M+H)^+$ 609.33017 found 609.33001.

(b) Conditions when Rh_2(*R*-BPCP)$_4$ was used as catalyst.



methyl (*S*)-2-(4-bromophenyl)-3-((8*S*,9*S*,10*R*,13*R*,14*S*,17*R*)-10,13-dimethyl-17-((*R*)-6-methylheptan-2-yl)-2,7,8,9,10,11,12,13,14,15,16,17-dodecahydro-1H-cyclopenta[a]phenanthren-3-yl)propanoate (**7.44**-mismatched diastereomer)

Prepared according to the general procedure for selective C–H functionalization using methyl 2-(4-bromophenyl)-2-diazoacetate (**7.1**) (0.4 mmol, 102 mg, 1.0 equiv), steroid (**7.43**) (183.5 mg, 1.2 equiv), Rh_2(*R*-BPCP)$_4$ (0.5 mol%, 3.5 mg). The crude residue was analyzed by ^{1}H NMR (the dr of product **7.44** is 1:6) and purified by flash column chromatography (hexanes/ethyl acetate = 50/1) to afford the combined diastereomers (216.2 mg, 89% combined yield). Note: the diastereomers were partially separated by flash column chromatography (hexanes/ethyl acetate = 100/1), and the mismatched product (**7.44**) was obtained (24 mg), and the absolute configuration of the new stereogenic center generated in the mismatched reactions was tentatively assigned as (*S*) by analogy. The characterization data for the mismatched product of (**7.44**), as follows:

Mp = 103-105 °C; $[\alpha]^{20}_{D:}$ -28.8° (*c* = 1.20, $CHCl_3$); ^1H NMR (400 MHz, $CDCl_3$): δ 7.43 (d, *J* = 8.4 Hz, 2H), 7.22 (d, *J* = 8.4 Hz, 2H), 5.73 (s, 1H), 5.32 (s, 1H), 3.77 (dd, *J* = 6.0, 9.2 Hz, 1H), 3.64 (s, 3H), 2.82 (dd, *J* = 9.6, 14.0 Hz, 1H), 2.40 (dd, *J* = 6.0, 14.0 Hz, 1H), 2.17-2.10 (m, 2H), 2.04-1.99 (m, 1H), 1.93-1.77 (m, 3H), 1.69-1.48 (m, 6H), 1,42-1.26 (m, 6H), 1.22-1.01 (m, 10H), 0.92 (d, *J* = 6.4 Hz, 3H), 0.88-0.86 (m, 9H), 0.70 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 173.7, 141.4, 137.9, 132.5, 131.6, 129.6, 126.7, 122.8, 121.2, 56.9, 56.1, 52.0, 49.9, 48.2, 42.4, 41.8, 39.7, 39.5, 36.2, 35.8, 34.7, 33.9, 31.8, 28.2, 27.9, 26.4, 24.2, 23.8, 22.8, 22.6, 21.0, 18.7, 11.9; IR (neat): 2934, 2867, 1736, 1488, 1432, 1154, 1074, 1011, 824, 756; HRMS (FTMS+p-NSI) calcd for $C_{37}H_{54}O_2Br$ $(M+H)^+$ 609.33017 found 609.32993.

(c) Conditions when Rh_2(*S*-DOSP)$_4$ was used as catalyst.

Prepared according to the general procedure for selective C–H functionalization using methyl 2-(4-bromophenyl)-2-diazoacetate (**7.1**) (0.4 mmol, 102 mg, 1.0 equiv), steroid (**7.43**) (183.5 mg, 1.2 equiv), Rh_2(*S*-DOSP)$_4$ (0.5 mol%, 3.8 mg). The crude residue was analyzed by ^1H NMR (the dr of product is 16:1) and then purified by flash column chromatography (hexanes/ethyl acetate = 50/1) to afford the combined diastereomers (209.1 mg, 86% combined yield).

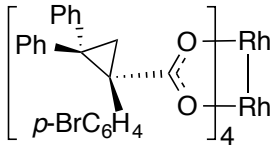
(d) Conditions when Rh_2(*R*-DOSP)$_4$ was used as catalyst.

Prepared according to the general procedure for selective C-H functionalization using methyl 2-(4-bromophenyl)-2-diazoacetate (**7.1**) (0.4 mmol, 102 mg, 1.0 equiv), steroid **7.43** (183.5 mg, 1.2 equiv), Rh_2(*R*-DOSP)$_4$ (0.5 mol%, 3.8 mg). The crude residue was analyzed by ^1H NMR (the dr of product is 1:3) and then purified by flash column

chromatography (hexanes/ethyl acetate = 50/1) to afford the combined diasteromers (199.4 mg, 82% combined yield).

APPENDIX

1: X-ray crystallographic structure of 3.19



3.19
Rh_2(*R*-BTPCP)$_4$

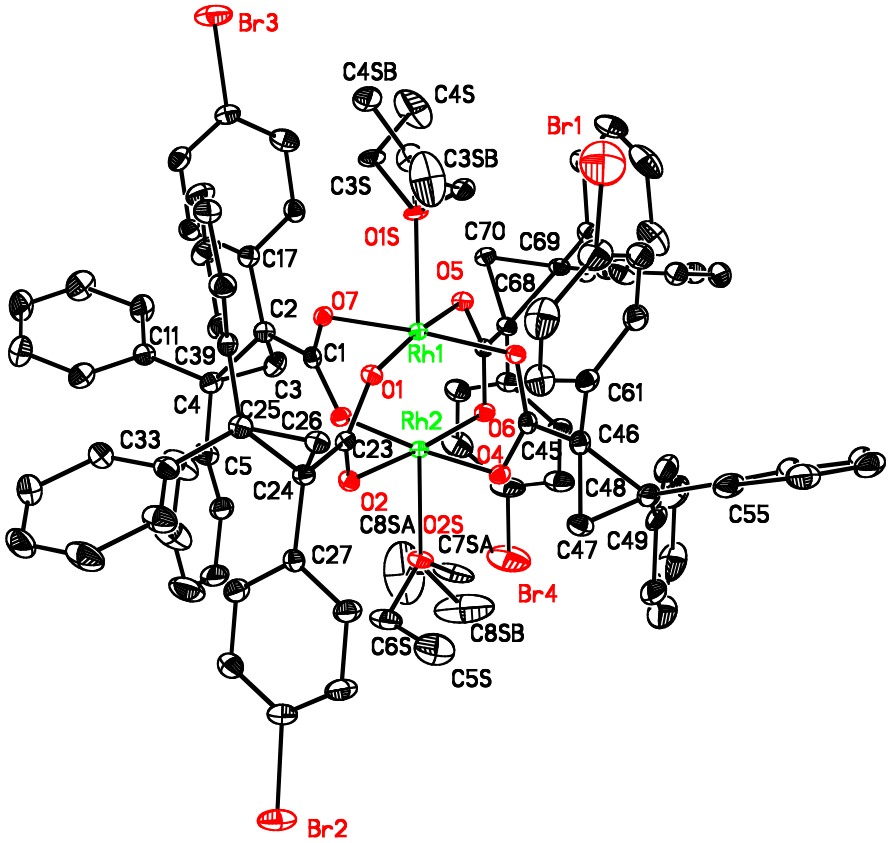


Table 1. Crystal data and structure refinement for **3.19**

Identification code	qin_3_27	
Empirical formula	C94.70 H80.75 Br4 O11.30 Rh2	
Formula weight	1925.00	
Temperature	173(2) K	
Wavelength	1.54178 Å	
Crystal system	Orthorhombic	
Space group	P2(1)2(1)2(1)	
Unit cell dimensions	a = 18.1690(5) Å	a= 90°.
	b = 21.4934(6) Å	b= 90°.
	c = 24.0740(6) Å	g = 90°.
Volume	9401.2(4) $Å^3$	
Z	4	
Density (calculated)	1.360 Mg/m^3	
Absorption coefficient	5.267 mm^{-1}	
F(000)	3877	
Crystal size	0.24 x 0.21 x 0.11 mm^3	
Theta range for data collection	3.05 to 69.59°.	
Index ranges	-21<=h<=17, -24<=k<=25, -28<=l<=27	
Reflections collected	64982	
Independent reflections	16806 [R(int) = 0.0284]	
Completeness to theta = 69.59°	96.6 %	
Absorption correction	Semi-empirical from equivalents	
Max. and min. transmission	0.6026 and 0.3621	
Refinement method	Full-matrix least-squares on F^2	
Data / restraints / parameters	16806 / 0 / 1057	
Goodness-of-fit on F^2	1.070	
Final R indices [I>2sigma(I)]	R1 = 0.0446, wR2 = 0.1319	
R indices (all data)	R1 = 0.0461, wR2 = 0.1338	
Absolute structure parameter	0.015(6)	
Largest diff. peak and hole	2.567 and -0.909 $e.Å^{-3}$	

Table 2. Atomic coordinates (x 10^4) and equivalent isotropic displacement parameters ($Å^2$x 10^3) for **3.19**. U(eq) is defined as one third of the trace of the orthogonalized U^{ij} tensor.

	x	y	z	U(eq)
Br(1)	-1693(1)	4688(1)	6952(1)	116(1)
Br(2)	3642(1)	7767(1)	4382(1)	60(1)
Br(3)	955(1)	7556(1)	10503(1)	70(1)
Br(4)	6927(1)	5336(1)	7910(1)	99(1)
C(1)	2915(3)	7030(2)	8121(2)	26(1)
C(2)	3210(3)	7432(2)	8587(2)	28(1)
C(3)	4025(3)	7374(3)	8697(2)	38(1)
C(4)	3756(3)	7967(2)	8442(2)	33(1)
C(5)	3919(4)	8083(3)	7834(2)	48(2)
C(6)	4622(5)	8008(3)	7643(3)	61(2)
C(7)	4792(8)	8135(4)	7088(5)	109(5)
C(8)	4254(10)	8372(5)	6737(4)	111(5)
C(9)	3554(7)	8430(5)	6938(3)	94(4)
C(10)	3374(5)	8298(4)	7478(3)	70(2)
C(11)	3735(3)	8555(2)	8791(2)	33(1)
C(12)	3557(4)	9127(3)	8553(3)	45(1)
C(13)	3543(4)	9670(3)	8860(3)	55(2)
C(14)	3700(5)	9656(3)	9415(3)	59(2)
C(15)	3876(5)	9106(4)	9656(3)	63(2)
C(16)	3892(4)	8550(3)	9350(3)	50(2)
C(17)	2675(3)	7494(2)	9058(2)	29(1)
C(18)	2167(3)	7980(2)	9094(2)	34(1)
C(19)	1666(3)	7999(3)	9517(2)	41(1)
C(20)	1654(3)	7533(3)	9912(2)	37(1)
C(21)	2148(3)	7053(3)	9890(2)	44(1)
C(22)	2664(3)	7036(2)	9466(2)	35(1)
C(23)	1816(2)	6846(2)	6728(2)	22(1)
C(24)	1439(3)	7219(2)	6281(2)	26(1)
C(25)	822(3)	7678(2)	6447(2)	30(1)
C(26)	649(3)	7081(2)	6149(2)	29(1)

C(27)	1950(3)	7380(2)	5803(2)	27(1)
C(28)	2419(3)	7881(3)	5824(2)	37(1)
C(29)	2915(3)	8007(3)	5411(2)	43(1)
C(30)	2946(3)	7622(3)	4964(2)	38(1)
C(31)	2478(4)	7119(3)	4912(2)	49(2)
C(32)	1982(3)	6995(3)	5338(2)	42(1)
C(33)	802(3)	8298(3)	6156(2)	36(1)
C(34)	1038(4)	8827(3)	6450(3)	50(2)
C(35)	1016(5)	9413(3)	6214(4)	70(2)
C(36)	780(5)	9480(4)	5656(4)	78(3)
C(37)	549(4)	8969(4)	5373(3)	69(2)
C(38)	555(4)	8372(4)	5610(3)	53(2)
C(39)	558(3)	7711(2)	7042(2)	30(1)
C(40)	-195(3)	7686(3)	7145(2)	39(1)
C(41)	-470(4)	7742(3)	7664(3)	48(1)
C(42)	15(4)	7799(3)	8122(3)	52(2)
C(43)	749(4)	7819(3)	8027(2)	51(2)
C(44)	1036(3)	7779(2)	7482(2)	36(1)
C(45)	2004(3)	5302(2)	6798(2)	24(1)
C(46)	1594(3)	4933(2)	6360(2)	29(1)
C(47)	1846(3)	5025(3)	5769(2)	36(1)
C(48)	2014(4)	4411(2)	6038(2)	36(1)
C(49)	2800(3)	4296(3)	6201(2)	38(1)
C(50)	2990(4)	4108(3)	6729(3)	50(1)
C(51)	3722(4)	3986(4)	6860(3)	61(2)
C(52)	4256(5)	4069(4)	6467(5)	80(3)
C(53)	4084(4)	4258(4)	5946(5)	71(2)
C(54)	3366(4)	4376(3)	5815(3)	55(2)
C(55)	1585(3)	3834(3)	5866(2)	44(1)
C(56)	1821(4)	3256(3)	6021(3)	53(2)
C(57)	1449(5)	2718(3)	5848(3)	66(2)
C(58)	830(5)	2772(4)	5507(3)	74(3)
C(59)	595(4)	3349(4)	5362(3)	62(2)
C(60)	949(4)	3887(4)	5531(2)	54(2)
C(61)	791(3)	4860(2)	6482(2)	32(1)
C(62)	536(3)	4406(3)	6852(2)	41(1)

C(63)	-189(4)	4361(3)	6991(3)	51(2)
C(64)	-677(4)	4763(4)	6766(4)	64(2)
C(65)	-437(4)	5240(4)	6406(4)	71(2)
C(66)	279(4)	5281(3)	6267(3)	49(1)
C(67)	3193(3)	5492(2)	8174(2)	24(1)
C(68)	3680(3)	5220(2)	8625(2)	26(1)
C(69)	3356(3)	4675(2)	8987(2)	29(1)
C(70)	3413(3)	5330(2)	9212(2)	29(1)
C(71)	4476(3)	5238(2)	8489(2)	32(1)
C(72)	4939(3)	5689(3)	8706(3)	44(1)
C(73)	5682(4)	5731(4)	8539(3)	62(2)
C(74)	5926(4)	5301(4)	8162(3)	59(2)
C(75)	5485(4)	4837(4)	7945(3)	52(2)
C(76)	4767(3)	4808(3)	8113(2)	39(1)
C(77)	3904(3)	4187(2)	9193(2)	30(1)
C(78)	4480(3)	4332(3)	9548(2)	39(1)
C(79)	4954(3)	3865(3)	9750(2)	43(1)
C(80)	4841(3)	3257(3)	9600(2)	42(1)
C(81)	4271(4)	3103(3)	9230(3)	47(1)
C(82)	3812(3)	3567(3)	9037(2)	39(1)
C(83)	2616(3)	4437(2)	8866(2)	32(1)
C(84)	2081(4)	4417(3)	9281(3)	46(1)
C(85)	1385(4)	4193(4)	9180(3)	59(2)
C(86)	1189(4)	3981(4)	8670(4)	68(2)
C(87)	1716(4)	3984(4)	8229(3)	62(2)
C(88)	2422(4)	4217(3)	8336(2)	45(1)
C(1S)	-308(8)	5952(6)	7830(7)	103(5)
C(2S)	304(4)	5640(3)	8069(3)	37(2)
C(3S)	808(7)	6336(6)	8774(4)	35(2)
C(4S)	880(14)	5921(9)	9258(6)	96(7)
C(5S)	3846(8)	6280(7)	5751(5)	86(4)
C(6S)	4111(5)	6656(5)	6184(3)	51(2)
C(7SA)	4749(6)	5985(8)	6829(6)	63(4)
C(7SB)	4540(40)	6318(11)	6900(30)	360(60)
C(8SA)	5273(18)	6413(15)	7124(17)	161(17)
C(8SB)	5304(16)	5910(20)	6733(10)	143(17)

C(3SB)	1034(14)	6002(14)	8875(10)	42(6)
C(4SB)	492(17)	6316(13)	9162(9)	49(6)
O(1)	1411(2)	6564(2)	7083(1)	25(1)
O(2)	2511(2)	6846(2)	6717(1)	27(1)
O(3)	1693(2)	5331(1)	7270(1)	26(1)
O(4)	2593(2)	5566(2)	6658(1)	25(1)
O(5)	2545(2)	5655(2)	8297(1)	25(1)
O(6)	3490(2)	5557(2)	7703(1)	26(1)
O(7)	2239(2)	6897(1)	8135(1)	24(1)
O(8)	3379(2)	6837(2)	7763(1)	28(1)
O(1S)	890(2)	6028(2)	8245(2)	28(1)
O(2S)	4075(3)	6285(3)	6677(2)	28(1)
Rh(1)	1933(1)	6109(1)	7718(1)	19(1)
Rh(2)	3031(1)	6199(1)	7190(1)	20(1)
O(1W)	7217(11)	7527(9)	7018(8)	58(5)
O(2W)	8118(6)	3278(4)	1350(4)	59(2)
O(3W)	8102(3)	6601(2)	7100(2)	62(1)

Table 3. Bond lengths [Å] and angles [°] for **3.19**.

Br(1)-C(64)	1.905(7)

Br(2)-C(30)	1.914(5)
Br(3)-C(20)	1.908(5)
Br(4)-C(74)	1.918(6)
C(1)-O(7)	1.260(6)
C(1)-O(8)	1.275(6)
C(1)-C(2)	1.514(6)
C(2)-C(17)	1.501(7)
C(2)-C(3)	1.509(7)
C(2)-C(4)	1.558(7)
C(3)-C(4)	1.496(8)
C(3)-H(3A)	0.9900
C(3)-H(3B)	0.9900
C(4)-C(5)	1.515(8)
C(4)-C(11)	1.518(7)
C(5)-C(6)	1.367(10)
C(5)-C(10)	1.388(11)
C(6)-C(7)	1.396(13)
C(6)-H(6A)	0.9500
C(7)-C(8)	1.39(2)
C(7)-H(7A)	0.9500
C(8)-C(9)	1.366(19)
C(8)-H(8A)	0.9500
C(9)-C(10)	1.372(11)
C(9)-H(9A)	0.9500
C(10)-H(10A)	0.9500
C(11)-C(16)	1.376(8)
C(11)-C(12)	1.396(9)
C(12)-C(13)	1.381(9)
C(12)-H(12A)	0.9500
C(13)-C(14)	1.367(10)
C(13)-H(13A)	0.9500
C(14)-C(15)	1.355(11)
C(14)-H(14A)	0.9500
C(15)-C(16)	1.402(9)
C(15)-H(15A)	0.9500
C(16)-H(16A)	0.9500

C(17)-C(22)	1.388(7)
C(17)-C(18)	1.398(7)
C(18)-C(19)	1.366(8)
C(18)-H(18A)	0.9500
C(19)-C(20)	1.380(8)
C(19)-H(19A)	0.9500
C(20)-C(21)	1.369(9)
C(21)-C(22)	1.389(8)
C(21)-H(21A)	0.9500
C(22)-H(22A)	0.9500
C(23)-O(2)	1.262(6)
C(23)-O(1)	1.280(6)
C(23)-C(24)	1.507(6)
C(24)-C(26)	1.500(7)
C(24)-C(27)	1.518(6)
C(24)-C(25)	1.546(7)
C(25)-C(26)	1.503(7)
C(25)-C(33)	1.505(7)
C(25)-C(39)	1.512(7)
C(26)-H(26A)	0.9900
C(26)-H(26B)	0.9900
C(27)-C(28)	1.375(8)
C(27)-C(32)	1.392(7)
C(28)-C(29)	1.367(8)
C(28)-H(28A)	0.9500
C(29)-C(30)	1.360(8)
C(29)-H(29A)	0.9500
C(30)-C(31)	1.379(9)
C(31)-C(32)	1.392(8)
C(31)-H(31A)	0.9500
C(32)-H(32A)	0.9500
C(33)-C(38)	1.397(9)
C(33)-C(34)	1.407(9)
C(34)-C(35)	1.382(9)
C(34)-H(34A)	0.9500
C(35)-C(36)	1.419(14)

C(35)-H(35A)	0.9500
C(36)-C(37)	1.360(15)
C(36)-H(36A)	0.9500
C(37)-C(38)	1.405(10)
C(37)-H(37A)	0.9500
C(38)-H(38A)	0.9500
C(39)-C(44)	1.378(8)
C(39)-C(40)	1.393(8)
C(40)-C(41)	1.351(8)
C(40)-H(40A)	0.9500
C(41)-C(42)	1.417(10)
C(41)-H(41A)	0.9500
C(42)-C(43)	1.353(10)
C(42)-H(42A)	0.9500
C(43)-C(44)	1.414(8)
C(43)-H(43A)	0.9500
C(44)-H(44A)	0.9500
C(45)-O(4)	1.258(6)
C(45)-O(3)	1.270(6)
C(45)-C(46)	1.515(6)
C(46)-C(61)	1.496(8)
C(46)-C(47)	1.506(7)
C(46)-C(48)	1.562(7)
C(47)-C(48)	1.502(8)
C(47)-H(47A)	0.9900
C(47)-H(47B)	0.9900
C(48)-C(49)	1.500(9)
C(48)-C(55)	1.523(7)
C(49)-C(50)	1.378(9)
C(49)-C(54)	1.398(8)
C(50)-C(51)	1.390(11)
C(50)-H(50A)	0.9500
C(51)-C(52)	1.368(13)
C(51)-H(51)	0.9500
C(52)-C(53)	1.354(15)
C(52)-H(52A)	0.9500

C(53)-C(54)	1.366(12)
C(53)-H(53A)	0.9500
C(54)-H(54A)	0.9500
C(55)-C(56)	1.368(10)
C(55)-C(60)	1.414(10)
C(56)-C(57)	1.403(10)
C(56)-H(56A)	0.9500
C(57)-C(58)	1.398(14)
C(57)-H(57A)	0.9500
C(58)-C(59)	1.356(14)
C(58)-H(58A)	0.9500
C(59)-C(60)	1.385(9)
C(59)-H(59A)	0.9500
C(60)-H(60A)	0.9500
C(61)-C(66)	1.398(9)
C(61)-C(62)	1.401(8)
C(62)-C(63)	1.362(9)
C(62)-H(62A)	0.9500
C(63)-C(64)	1.352(12)
C(63)-H(63A)	0.9500
C(64)-C(65)	1.413(13)
C(65)-C(66)	1.346(11)
C(65)-H(65A)	0.9500
C(66)-H(66A)	0.9500
C(67)-O(6)	1.263(6)
C(67)-O(5)	1.265(6)
C(67)-C(68)	1.518(6)
C(68)-C(71)	1.483(7)
C(68)-C(70)	1.512(6)
C(68)-C(69)	1.574(6)
C(69)-C(83)	1.468(8)
C(69)-C(70)	1.512(7)
C(69)-C(77)	1.528(7)
C(70)-H(70A)	0.9900
C(70)-H(70B)	0.9900
C(71)-C(72)	1.384(8)

C(71)-C(76)	1.398(8)
C(72)-C(73)	1.413(10)
C(72)-H(72A)	0.9500
C(73)-C(74)	1.369(12)
C(73)-H(73A)	0.9500
C(74)-C(75)	1.382(12)
C(75)-C(76)	1.369(9)
C(75)-H(75A)	0.9500
C(76)-H(76A)	0.9500
C(77)-C(78)	1.387(8)
C(77)-C(82)	1.396(8)
C(78)-C(79)	1.407(8)
C(78)-H(78A)	0.9500
C(79)-C(80)	1.371(9)
C(79)-H(79A)	0.9500
C(80)-C(81)	1.407(9)
C(80)-H(80A)	0.9500
C(81)-C(82)	1.380(8)
C(81)-H(81A)	0.9500
C(82)-H(82A)	0.9500
C(83)-C(84)	1.394(8)
C(83)-C(88)	1.407(8)
C(84)-C(85)	1.375(10)
C(84)-H(84A)	0.9500
C(85)-C(86)	1.356(12)
C(85)-H(85A)	0.9500
C(86)-C(87)	1.429(12)
C(86)-H(86A)	0.9500
C(87)-C(88)	1.401(9)
C(87)-H(87A)	0.9500
C(88)-H(88A)	0.9500
C(1S)-C(2S)	1.420(14)
C(1S)-H(1SA)	0.9800
C(1S)-H(1SB)	0.9800
C(1S)-H(1SC)	0.9800
C(2S)-O(1S)	1.417(7)

C(2S)-H(2S1)	0.9900
C(2S)-H(2S2)	0.9900
C(3S)-O(1S)	1.442(9)
C(3S)-C(4S)	1.474(17)
C(3S)-H(3SA)	0.9900
C(3S)-H(3SB)	0.9900
C(4S)-H(4SA)	0.9800
C(4S)-H(4SB)	0.9800
C(4S)-H(4SC)	0.9800
C(5S)-C(6S)	1.404(17)
C(5S)-H(5SA)	0.9800
C(5S)-H(5SB)	0.9800
C(5S)-H(5SC)	0.9800
C(6S)-O(2S)	1.433(9)
C(6S)-C(7SB)	2.03(8)
C(6S)-H(6SA)	0.9900
C(6S)-H(6SB)	0.9900
C(7SA)-O(2S)	1.432(11)
C(7SA)-C(8SA)	1.50(3)
C(7SA)-H(7S1)	0.9900
C(7SA)-H(7S2)	0.9900
C(7SB)-O(2S)	1.01(10)
C(7SB)-C(8SB)	1.69(6)
C(7SB)-H(7S3)	0.9900
C(7SB)-H(7S4)	0.9900
C(8SA)-H(8S1)	0.9800
C(8SA)-H(8S2)	0.9800
C(8SA)-H(8S3)	0.9800
C(8SB)-H(8S4)	0.9800
C(8SB)-H(8S5)	0.9800
C(8SB)-H(8S6)	0.9800

C(3SB)-C(4SB)	1.38(4)

C(3SB)-O(1S)	1.54(2)
C(3SB)-H(3S1)	0.9900
C(3SB)-H(3S2)	0.9900
C(4SB)-H(4SD)	0.9800
C(4SB)-H(4SE)	0.9800
C(4SB)-H(4SF)	0.9800
O(1)-Rh(1)	2.049(3)
O(2)-Rh(2)	2.031(3)
O(3)-Rh(1)	2.038(3)
O(4)-Rh(2)	2.032(3)
O(5)-Rh(1)	2.032(3)
O(6)-Rh(2)	2.032(3)
O(7)-Rh(1)	2.046(3)
O(8)-Rh(2)	2.045(3)
O(1S)-Rh(1)	2.287(4)
O(2S)-Rh(2)	2.270(5)
Rh(1)-Rh(2)	2.3746(4)

O(7)-C(1)-O(8)	126.0(4)
O(7)-C(1)-C(2)	117.1(4)
O(8)-C(1)-C(2)	116.9(4)
C(17)-C(2)-C(3)	120.8(4)
C(17)-C(2)-C(1)	112.4(4)
C(3)-C(2)-C(1)	115.6(4)
C(17)-C(2)-C(4)	121.1(4)
C(3)-C(2)-C(4)	58.4(4)
C(1)-C(2)-C(4)	118.7(4)
C(4)-C(3)-C(2)	62.5(3)
C(4)-C(3)-H(3A)	117.5
C(2)-C(3)-H(3A)	117.5
C(4)-C(3)-H(3B)	117.5
C(2)-C(3)-H(3B)	117.5
H(3A)-C(3)-H(3B)	114.6
C(3)-C(4)-C(5)	118.2(5)
C(3)-C(4)-C(11)	119.3(4)
C(5)-C(4)-C(11)	113.8(5)

C(3)-C(4)-C(2)	59.2(4)
C(5)-C(4)-C(2)	117.6(4)
C(11)-C(4)-C(2)	118.3(4)
C(6)-C(5)-C(10)	119.9(7)
C(6)-C(5)-C(4)	119.3(7)
C(10)-C(5)-C(4)	120.8(6)
C(5)-C(6)-C(7)	120.4(11)
C(5)-C(6)-H(6A)	119.8
C(7)-C(6)-H(6A)	119.8
C(8)-C(7)-C(6)	119.8(11)
C(8)-C(7)-H(7A)	120.1
C(6)-C(7)-H(7A)	120.1
C(9)-C(8)-C(7)	118.3(8)
C(9)-C(8)-H(8A)	120.9
C(7)-C(8)-H(8A)	120.9
C(8)-C(9)-C(10)	122.6(11)
C(8)-C(9)-H(9A)	118.7
C(10)-C(9)-H(9A)	118.7
C(9)-C(10)-C(5)	118.9(10)
C(9)-C(10)-H(10A)	120.5
C(5)-C(10)-H(10A)	120.5
C(16)-C(11)-C(12)	117.2(5)
C(16)-C(11)-C(4)	122.1(5)
C(12)-C(11)-C(4)	120.8(5)
C(13)-C(12)-C(11)	121.9(6)
C(13)-C(12)-H(12A)	119.0
C(11)-C(12)-H(12A)	119.0
C(14)-C(13)-C(12)	120.0(7)
C(14)-C(13)-H(13A)	120.0
C(12)-C(13)-H(13A)	120.0
C(15)-C(14)-C(13)	119.1(6)
C(15)-C(14)-H(14A)	120.5
C(13)-C(14)-H(14A)	120.5
C(14)-C(15)-C(16)	121.6(6)
C(14)-C(15)-H(15A)	119.2
C(16)-C(15)-H(15A)	119.2

C(11)-C(16)-C(15)	120.1(6)
C(11)-C(16)-H(16A)	119.9
C(15)-C(16)-H(16A)	119.9
C(22)-C(17)-C(18)	118.5(5)
C(22)-C(17)-C(2)	118.7(5)
C(18)-C(17)-C(2)	122.7(4)
C(19)-C(18)-C(17)	120.4(5)
C(19)-C(18)-H(18A)	119.8
C(17)-C(18)-H(18A)	119.8
C(18)-C(19)-C(20)	120.2(5)
C(18)-C(19)-H(19A)	119.9
C(20)-C(19)-H(19A)	119.9
C(21)-C(20)-C(19)	120.7(5)
C(21)-C(20)-Br(3)	118.9(4)
C(19)-C(20)-Br(3)	120.4(4)
C(20)-C(21)-C(22)	119.4(5)
C(20)-C(21)-H(21A)	120.3
C(22)-C(21)-H(21A)	120.3
C(17)-C(22)-C(21)	120.7(5)
C(17)-C(22)-H(22A)	119.6
C(21)-C(22)-H(22A)	119.6
O(2)-C(23)-O(1)	126.1(4)
O(2)-C(23)-C(24)	116.1(4)
O(1)-C(23)-C(24)	117.8(4)
C(26)-C(24)-C(23)	118.8(4)
C(26)-C(24)-C(27)	118.0(4)
C(23)-C(24)-C(27)	112.6(4)
C(26)-C(24)-C(25)	59.1(3)
C(23)-C(24)-C(25)	119.0(4)
C(27)-C(24)-C(25)	119.6(4)
C(26)-C(25)-C(33)	121.9(4)
C(26)-C(25)-C(39)	115.2(4)
C(33)-C(25)-C(39)	113.1(4)
C(26)-C(25)-C(24)	58.9(3)
C(33)-C(25)-C(24)	117.5(4)
C(39)-C(25)-C(24)	120.2(4)

C(24)-C(26)-C(25)	62.0(3)
C(24)-C(26)-H(26A)	117.6
C(25)-C(26)-H(26A)	117.6
C(24)-C(26)-H(26B)	117.6
C(25)-C(26)-H(26B)	117.6
H(26A)-C(26)-H(26B)	114.7
C(28)-C(27)-C(32)	117.9(5)
C(28)-C(27)-C(24)	122.0(4)
C(32)-C(27)-C(24)	119.9(4)
C(29)-C(28)-C(27)	122.5(5)
C(29)-C(28)-H(28A)	118.7
C(27)-C(28)-H(28A)	118.7
C(30)-C(29)-C(28)	118.8(5)
C(30)-C(29)-H(29A)	120.6
C(28)-C(29)-H(29A)	120.6
C(29)-C(30)-C(31)	121.5(5)
C(29)-C(30)-Br(2)	120.5(4)
C(31)-C(30)-Br(2)	118.0(4)
C(30)-C(31)-C(32)	118.8(5)
C(30)-C(31)-H(31A)	120.6
C(32)-C(31)-H(31A)	120.6
C(31)-C(32)-C(27)	120.4(5)
C(31)-C(32)-H(32A)	119.8
C(27)-C(32)-H(32A)	119.8
C(38)-C(33)-C(34)	118.7(6)
C(38)-C(33)-C(25)	123.1(6)
C(34)-C(33)-C(25)	118.3(5)
C(35)-C(34)-C(33)	121.4(7)
C(35)-C(34)-H(34A)	119.3
C(33)-C(34)-H(34A)	119.3
C(34)-C(35)-C(36)	119.4(8)
C(34)-C(35)-H(35A)	120.3
C(36)-C(35)-H(35A)	120.3
C(37)-C(36)-C(35)	119.0(6)
C(37)-C(36)-H(36A)	120.5
C(35)-C(36)-H(36A)	120.5

C(36)-C(37)-C(38)	122.2(8)
C(36)-C(37)-H(37A)	118.9
C(38)-C(37)-H(37A)	118.9
C(33)-C(38)-C(37)	119.2(8)
C(33)-C(38)-H(38A)	120.4
C(37)-C(38)-H(38A)	120.4
C(44)-C(39)-C(40)	119.0(5)
C(44)-C(39)-C(25)	122.3(5)
C(40)-C(39)-C(25)	118.6(5)
C(41)-C(40)-C(39)	121.7(6)
C(41)-C(40)-H(40A)	119.1
C(39)-C(40)-H(40A)	119.1
C(40)-C(41)-C(42)	119.8(6)
C(40)-C(41)-H(41A)	120.1
C(42)-C(41)-H(41A)	120.1
C(43)-C(42)-C(41)	118.9(5)
C(43)-C(42)-H(42A)	120.6
C(41)-C(42)-H(42A)	120.6
C(42)-C(43)-C(44)	121.3(6)
C(42)-C(43)-H(43A)	119.3
C(44)-C(43)-H(43A)	119.3
C(39)-C(44)-C(43)	119.2(6)
C(39)-C(44)-H(44A)	120.4
C(43)-C(44)-H(44A)	120.4
O(4)-C(45)-O(3)	126.7(4)
O(4)-C(45)-C(46)	117.9(4)
O(3)-C(45)-C(46)	115.4(4)
C(61)-C(46)-C(47)	119.7(4)
C(61)-C(46)-C(45)	113.4(4)
C(47)-C(46)-C(45)	116.0(4)
C(61)-C(46)-C(48)	119.9(4)
C(47)-C(46)-C(48)	58.6(3)
C(45)-C(46)-C(48)	118.8(4)
C(48)-C(47)-C(46)	62.6(3)
C(48)-C(47)-H(47A)	117.5
C(46)-C(47)-H(47A)	117.5

C(48)-C(47)-H(47B)	117.5
C(46)-C(47)-H(47B)	117.5
H(47A)-C(47)-H(47B)	114.6
C(49)-C(48)-C(47)	116.9(5)
C(49)-C(48)-C(55)	115.1(5)
C(47)-C(48)-C(55)	119.6(5)
C(49)-C(48)-C(46)	117.0(4)
C(47)-C(48)-C(46)	58.9(3)
C(55)-C(48)-C(46)	118.0(5)
C(50)-C(49)-C(54)	117.7(6)
C(50)-C(49)-C(48)	121.9(5)
C(54)-C(49)-C(48)	120.3(6)
C(49)-C(50)-C(51)	120.3(7)
C(49)-C(50)-H(50A)	119.8
C(51)-C(50)-H(50A)	119.8
C(52)-C(51)-C(50)	119.8(8)
C(52)-C(51)-H(51)	120.1
C(50)-C(51)-H(51)	120.1
C(53)-C(52)-C(51)	121.0(8)
C(53)-C(52)-H(52A)	119.5
C(51)-C(52)-H(52A)	119.5
C(52)-C(53)-C(54)	119.4(8)
C(52)-C(53)-H(53A)	120.3
C(54)-C(53)-H(53A)	120.3
C(53)-C(54)-C(49)	121.7(8)
C(53)-C(54)-H(54A)	119.1
C(49)-C(54)-H(54A)	119.1
C(56)-C(55)-C(60)	119.1(6)
C(56)-C(55)-C(48)	120.3(6)
C(60)-C(55)-C(48)	120.6(6)
C(55)-C(56)-C(57)	121.1(8)
C(55)-C(56)-H(56A)	119.4
C(57)-C(56)-H(56A)	119.4
C(58)-C(57)-C(56)	119.6(8)
C(58)-C(57)-H(57A)	120.2
C(56)-C(57)-H(57A)	120.2

C(59)-C(58)-C(57)	118.8(6)
C(59)-C(58)-H(58A)	120.6
C(57)-C(58)-H(58A)	120.6
C(58)-C(59)-C(60)	122.8(8)
C(58)-C(59)-H(59A)	118.6
C(60)-C(59)-H(59A)	118.6
C(59)-C(60)-C(55)	118.6(8)
C(59)-C(60)-H(60A)	120.7
C(55)-C(60)-H(60A)	120.7
C(66)-C(61)-C(62)	117.8(5)
C(66)-C(61)-C(46)	120.6(5)
C(62)-C(61)-C(46)	121.4(5)
C(63)-C(62)-C(61)	121.7(6)
C(63)-C(62)-H(62A)	119.1
C(61)-C(62)-H(62A)	119.1
C(64)-C(63)-C(62)	119.4(7)
C(64)-C(63)-H(63A)	120.3
C(62)-C(63)-H(63A)	120.3
C(63)-C(64)-C(65)	120.5(6)
C(63)-C(64)-Br(1)	119.2(6)
C(65)-C(64)-Br(1)	120.4(6)
C(66)-C(65)-C(64)	119.9(7)
C(66)-C(65)-H(65A)	120.0
C(64)-C(65)-H(65A)	120.0
C(65)-C(66)-C(61)	120.6(7)
C(65)-C(66)-H(66A)	119.7
C(61)-C(66)-H(66A)	119.7
O(6)-C(67)-O(5)	125.4(4)
O(6)-C(67)-C(68)	115.8(4)
O(5)-C(67)-C(68)	118.8(4)
C(71)-C(68)-C(70)	121.0(4)
C(71)-C(68)-C(67)	113.6(4)
C(70)-C(68)-C(67)	114.9(4)
C(71)-C(68)-C(69)	120.4(4)
C(70)-C(68)-C(69)	58.6(3)
C(67)-C(68)-C(69)	117.7(4)

C(83)-C(69)-C(70)	117.2(4)
C(83)-C(69)-C(77)	115.0(4)
C(70)-C(69)-C(77)	118.6(4)
C(83)-C(69)-C(68)	119.5(4)
C(70)-C(69)-C(68)	58.6(3)
C(77)-C(69)-C(68)	116.6(4)
C(68)-C(70)-C(69)	62.8(3)
C(68)-C(70)-H(70A)	117.5
C(69)-C(70)-H(70A)	117.5
C(68)-C(70)-H(70B)	117.5
C(69)-C(70)-H(70B)	117.5
H(70A)-C(70)-H(70B)	114.6
C(72)-C(71)-C(76)	118.5(5)
C(72)-C(71)-C(68)	121.8(5)
C(76)-C(71)-C(68)	119.6(5)
C(71)-C(72)-C(73)	121.2(6)
C(71)-C(72)-H(72A)	119.4
C(73)-C(72)-H(72A)	119.4
C(74)-C(73)-C(72)	117.0(7)
C(74)-C(73)-H(73A)	121.5
C(72)-C(73)-H(73A)	121.5
C(73)-C(74)-C(75)	123.4(6)
C(73)-C(74)-Br(4)	119.3(6)
C(75)-C(74)-Br(4)	117.3(6)
C(76)-C(75)-C(74)	118.3(7)
C(76)-C(75)-H(75A)	120.9
C(74)-C(75)-H(75A)	120.9
C(75)-C(76)-C(71)	121.5(6)
C(75)-C(76)-H(76A)	119.3
C(71)-C(76)-H(76A)	119.3
C(78)-C(77)-C(82)	118.0(5)
C(78)-C(77)-C(69)	122.5(5)
C(82)-C(77)-C(69)	119.4(5)
C(77)-C(78)-C(79)	121.0(6)
C(77)-C(78)-H(78A)	119.5
C(79)-C(78)-H(78A)	119.5

C(80)-C(79)-C(78)	119.8(6)
C(80)-C(79)-H(79A)	120.1
C(78)-C(79)-H(79A)	120.1
C(79)-C(80)-C(81)	120.1(5)
C(79)-C(80)-H(80A)	119.9
C(81)-C(80)-H(80A)	119.9
C(82)-C(81)-C(80)	119.2(6)
C(82)-C(81)-H(81A)	120.4
C(80)-C(81)-H(81A)	120.4
C(81)-C(82)-C(77)	121.8(6)
C(81)-C(82)-H(82A)	119.1
C(77)-C(82)-H(82A)	119.1
C(84)-C(83)-C(88)	117.8(5)
C(84)-C(83)-C(69)	120.5(5)
C(88)-C(83)-C(69)	121.7(5)
C(85)-C(84)-C(83)	121.6(6)
C(85)-C(84)-H(84A)	119.2
C(83)-C(84)-H(84A)	119.2
C(86)-C(85)-C(84)	121.3(7)
C(86)-C(85)-H(85A)	119.3
C(84)-C(85)-H(85A)	119.3
C(85)-C(86)-C(87)	119.6(6)
C(85)-C(86)-H(86A)	120.2
C(87)-C(86)-H(86A)	120.2
C(88)-C(87)-C(86)	118.7(7)
C(88)-C(87)-H(87A)	120.7
C(86)-C(87)-H(87A)	120.7
C(87)-C(88)-C(83)	121.0(7)
C(87)-C(88)-H(88A)	119.5
C(83)-C(88)-H(88A)	119.5
C(2S)-C(1S)-H(1SA)	109.5
C(2S)-C(1S)-H(1SB)	109.5
H(1SA)-C(1S)-H(1SB)	109.5
C(2S)-C(1S)-H(1SC)	109.5
H(1SA)-C(1S)-H(1SC)	109.5
H(1SB)-C(1S)-H(1SC)	109.5

O(1S)-C(2S)-C(1S)	115.7(7)
O(1S)-C(2S)-H(2S1)	108.4
C(1S)-C(2S)-H(2S1)	108.4
O(1S)-C(2S)-H(2S2)	108.4
C(1S)-C(2S)-H(2S2)	108.4
H(2S1)-C(2S)-H(2S2)	107.4
O(1S)-C(3S)-C(4S)	114.3(12)
O(1S)-C(3S)-H(3SA)	108.7
C(4S)-C(3S)-H(3SA)	108.7
O(1S)-C(3S)-H(3SB)	108.7
C(4S)-C(3S)-H(3SB)	108.7
H(3SA)-C(3S)-H(3SB)	107.6
C(3S)-C(4S)-H(4SA)	109.5
C(3S)-C(4S)-H(4SB)	109.5
H(4SA)-C(4S)-H(4SB)	109.5
C(3S)-C(4S)-H(4SC)	109.5
H(4SA)-C(4S)-H(4SC)	109.5
H(4SB)-C(4S)-H(4SC)	109.5
C(6S)-C(5S)-H(5SA)	109.5
C(6S)-C(5S)-H(5SB)	109.5
H(5SA)-C(5S)-H(5SB)	109.5
C(6S)-C(5S)-H(5SC)	109.5
H(5SA)-C(5S)-H(5SC)	109.5
H(5SB)-C(5S)-H(5SC)	109.5
C(5S)-C(6S)-O(2S)	106.1(9)
C(5S)-C(6S)-C(7SB)	123.8(13)
O(2S)-C(6S)-C(7SB)	27.4(16)
C(5S)-C(6S)-H(6SA)	110.5
O(2S)-C(6S)-H(6SA)	110.5
C(7SB)-C(6S)-H(6SA)	115.3
C(5S)-C(6S)-H(6SB)	110.5
O(2S)-C(6S)-H(6SB)	110.5
C(7SB)-C(6S)-H(6SB)	83.9
H(6SA)-C(6S)-H(6SB)	108.7
O(2S)-C(7SA)-C(8SA)	112.7(17)
O(2S)-C(7SA)-H(7S1)	109.0

C(8SA)-C(7SA)-H(7S1)	109.0
O(2S)-C(7SA)-H(7S2)	109.0
C(8SA)-C(7SA)-H(7S2)	109.0
H(7S1)-C(7SA)-H(7S2)	107.8
O(2S)-C(7SB)-C(8SB)	121(4)
O(2S)-C(7SB)-C(6S)	41(3)
C(8SB)-C(7SB)-C(6S)	107(2)
O(2S)-C(7SB)-H(7S3)	107.0
C(8SB)-C(7SB)-H(7S3)	107.0
C(6S)-C(7SB)-H(7S3)	143.0
O(2S)-C(7SB)-H(7S4)	107.0
C(8SB)-C(7SB)-H(7S4)	107.0
C(6S)-C(7SB)-H(7S4)	76.3
H(7S3)-C(7SB)-H(7S4)	106.7
C(7SA)-C(8SA)-H(8S1)	109.5
C(7SA)-C(8SA)-H(8S2)	109.5
H(8S1)-C(8SA)-H(8S2)	109.5
C(7SA)-C(8SA)-H(8S3)	109.5
H(8S1)-C(8SA)-H(8S3)	109.5
H(8S2)-C(8SA)-H(8S3)	109.5
C(7SB)-C(8SB)-H(8S4)	109.5
C(7SB)-C(8SB)-H(8S5)	109.5
H(8S4)-C(8SB)-H(8S5)	109.5
C(7SB)-C(8SB)-H(8S6)	109.5
H(8S4)-C(8SB)-H(8S6)	109.5
H(8S5)-C(8SB)-H(8S6)	109.5
C(4SB)-C(3SB)-O(1S)	111(2)
C(4SB)-C(3SB)-H(3S1)	109.5
O(1S)-C(3SB)-H(3S1)	109.5
C(4SB)-C(3SB)-H(3S2)	109.5
O(1S)-C(3SB)-H(3S2)	109.5
H(3S1)-C(3SB)-H(3S2)	108.1
C(3SB)-C(4SB)-H(4SD)	109.5
C(3SB)-C(4SB)-H(4SE)	109.5
H(4SD)-C(4SB)-H(4SE)	109.5
C(3SB)-C(4SB)-H(4SF)	109.5

H(4SD)-C(4SB)-H(4SF)	109.5
H(4SE)-C(4SB)-H(4SF)	109.5
C(23)-O(1)-Rh(1)	117.3(3)
C(23)-O(2)-Rh(2)	116.9(3)
C(45)-O(3)-Rh(1)	114.8(3)
C(45)-O(4)-Rh(2)	117.8(3)
C(67)-O(5)-Rh(1)	118.8(3)
C(67)-O(6)-Rh(2)	116.4(3)
C(1)-O(7)-Rh(1)	116.1(3)
C(1)-O(8)-Rh(2)	118.0(3)
C(2S)-O(1S)-C(3S)	117.2(6)
C(2S)-O(1S)-C(3SB)	113.7(12)
C(3S)-O(1S)-C(3SB)	33.4(10)
C(2S)-O(1S)-Rh(1)	120.0(3)
C(3S)-O(1S)-Rh(1)	122.7(5)
C(3SB)-O(1S)-Rh(1)	114.1(10)
C(7SB)-O(2S)-C(7SA)	34.6(15)
C(7SB)-O(2S)-C(6S)	111.7(17)
C(7SA)-O(2S)-C(6S)	115.1(6)
C(7SB)-O(2S)-Rh(2)	114.4(15)
C(7SA)-O(2S)-Rh(2)	122.6(5)
C(6S)-O(2S)-Rh(2)	122.2(4)
O(5)-Rh(1)-O(3)	94.97(13)
O(5)-Rh(1)-O(7)	84.99(13)
O(3)-Rh(1)-O(7)	175.94(13)
O(5)-Rh(1)-O(1)	174.01(13)
O(3)-Rh(1)-O(1)	84.07(13)
O(7)-Rh(1)-O(1)	95.55(13)
O(5)-Rh(1)-O(1S)	92.08(14)
O(3)-Rh(1)-O(1S)	93.09(13)
O(7)-Rh(1)-O(1S)	90.96(13)
O(1)-Rh(1)-O(1S)	93.88(15)
O(5)-Rh(1)-Rh(2)	86.96(9)
O(3)-Rh(1)-Rh(2)	87.90(9)
O(7)-Rh(1)-Rh(2)	88.05(9)
O(1)-Rh(1)-Rh(2)	87.09(9)

O(1S)-Rh(1)-Rh(2)	178.68(10)
O(2)-Rh(2)-O(6)	175.83(13)
O(2)-Rh(2)-O(4)	85.58(13)
O(6)-Rh(2)-O(4)	95.06(13)
O(2)-Rh(2)-O(8)	93.63(14)
O(6)-Rh(2)-O(8)	85.34(13)
O(4)-Rh(2)-O(8)	174.62(13)
O(2)-Rh(2)-O(2S)	91.66(16)
O(6)-Rh(2)-O(2S)	92.44(16)
O(4)-Rh(2)-O(2S)	92.21(17)
O(8)-Rh(2)-O(2S)	93.13(18)
O(2)-Rh(2)-Rh(1)	88.00(10)
O(6)-Rh(2)-Rh(1)	87.92(9)
O(4)-Rh(2)-Rh(1)	87.34(9)
O(8)-Rh(2)-Rh(1)	87.31(9)
O(2S)-Rh(2)-Rh(1)	179.46(13)

Symmetry transformations used to generate equivalent atoms:

Table 4. Anisotropic displacement parameters ($Å^2 x\ 10^3$) for **3.19**. The anisotropic displacement factor exponent takes the form: $-2p^2[\ h^2\ a^{*2}U^{11} + ...\ + 2\ h\ k\ a^*\ b^*\ U^{12}\ ]$

	U^{11}	U^{22}	U^{33}	U^{23}	U^{13}	U^{12}
Br(1)	34(1)	112(1)	202(2)	-14(1)	30(1)	-10(1)
Br(2)	46(1)	94(1)	38(1)	-4(1)	15(1)	-18(1)
Br(3)	62(1)	106(1)	42(1)	15(1)	22(1)	15(1)
Br(4)	32(1)	157(1)	106(1)	37(1)	23(1)	3(1)
C(1)	31(3)	23(2)	25(2)	0(2)	-5(2)	-1(2)
C(2)	23(3)	32(2)	27(2)	-2(2)	-5(2)	-4(2)
C(3)	36(3)	42(3)	37(3)	-11(2)	-8(2)	6(2)
C(4)	27(3)	39(3)	34(3)	-11(2)	1(2)	-9(2)
C(5)	62(4)	44(3)	38(3)	-13(2)	10(3)	-32(3)
C(6)	81(5)	41(3)	62(4)	-20(3)	36(4)	-25(3)

C(7)	162(12)	57(5)	109(9)	-28(5)	103(9)	-41(6)
C(8)	205(15)	82(7)	46(5)	-10(4)	46(7)	-63(8)
C(9)	151(10)	95(7)	36(4)	6(4)	-19(5)	-69(7)
C(10)	87(6)	80(5)	43(3)	6(3)	-19(3)	-55(4)
C(11)	31(3)	35(3)	34(3)	-7(2)	0(2)	-10(2)
C(12)	41(4)	52(3)	43(3)	-9(3)	-4(2)	1(3)
C(13)	65(5)	43(3)	57(4)	-8(3)	-10(3)	9(3)
C(14)	77(5)	41(3)	60(4)	-16(3)	-10(4)	-12(3)
C(15)	79(6)	68(5)	42(3)	-22(3)	-15(3)	-10(4)
C(16)	69(4)	44(3)	37(3)	-9(2)	-13(3)	-3(3)
C(17)	31(3)	33(2)	23(2)	-6(2)	-5(2)	-5(2)
C(18)	38(3)	34(3)	30(2)	7(2)	2(2)	5(2)
C(19)	37(3)	38(3)	47(3)	-7(2)	4(2)	9(2)
C(20)	36(3)	46(3)	28(2)	-2(2)	6(2)	2(2)
C(21)	41(3)	61(4)	30(3)	12(2)	-6(2)	-5(3)
C(22)	42(3)	31(2)	31(2)	3(2)	-4(2)	0(2)
C(23)	21(3)	25(2)	21(2)	-1(2)	-2(2)	3(2)
C(24)	25(3)	30(2)	23(2)	5(2)	0(2)	5(2)
C(25)	21(2)	35(3)	33(2)	7(2)	-2(2)	8(2)
C(26)	23(3)	34(2)	29(2)	3(2)	-1(2)	0(2)
C(27)	27(2)	27(2)	26(2)	5(2)	-4(2)	5(2)
C(28)	34(3)	41(3)	36(3)	-6(2)	4(2)	-4(2)
C(29)	44(4)	40(3)	44(3)	4(2)	4(2)	-6(2)
C(30)	29(3)	55(3)	28(2)	4(2)	3(2)	-3(2)
C(31)	50(4)	64(4)	33(3)	-11(3)	15(3)	-15(3)
C(32)	41(3)	49(3)	36(3)	-8(2)	11(2)	-11(3)
C(33)	28(3)	38(3)	43(3)	12(2)	9(2)	8(2)
C(34)	59(4)	36(3)	53(3)	5(3)	17(3)	0(3)
C(35)	90(6)	37(3)	82(5)	9(3)	32(5)	8(3)
C(36)	87(6)	56(5)	92(6)	44(5)	42(5)	35(4)
C(37)	58(5)	83(6)	66(4)	47(4)	11(4)	21(4)
C(38)	41(4)	67(4)	51(4)	24(3)	4(3)	11(3)
C(39)	33(3)	24(2)	32(2)	4(2)	3(2)	9(2)
C(40)	32(3)	43(3)	41(3)	4(2)	3(2)	2(2)
C(41)	44(4)	44(3)	55(3)	5(3)	18(3)	1(2)
C(42)	68(5)	52(3)	36(3)	1(3)	20(3)	13(3)

C(43)	65(5)	58(4)	29(3)	-7(2)	-5(3)	18(3)
C(44)	40(3)	32(3)	36(3)	-1(2)	1(2)	11(2)
C(45)	27(2)	22(2)	24(2)	-2(2)	-6(2)	-1(2)
C(46)	31(3)	28(2)	29(2)	-4(2)	-5(2)	-4(2)
C(47)	40(3)	44(3)	25(2)	-2(2)	0(2)	-15(2)
C(48)	42(3)	36(3)	31(2)	-10(2)	4(2)	-11(2)
C(49)	35(3)	34(3)	43(3)	-18(2)	8(2)	-3(2)
C(50)	55(4)	44(3)	52(3)	-14(2)	3(3)	2(3)
C(51)	52(4)	62(4)	69(4)	-12(3)	-8(3)	20(3)
C(52)	36(5)	70(5)	132(9)	-29(5)	2(5)	14(3)
C(53)	33(4)	66(5)	116(7)	-20(5)	25(4)	2(3)
C(54)	53(4)	48(3)	65(4)	-14(3)	25(3)	-6(3)
C(55)	52(4)	46(3)	34(3)	-21(2)	20(2)	-21(3)
C(56)	59(4)	43(3)	56(4)	-20(3)	25(3)	-14(3)
C(57)	79(6)	47(4)	73(5)	-21(3)	33(4)	-18(4)
C(58)	81(6)	81(6)	60(4)	-44(4)	36(4)	-51(5)
C(59)	62(5)	81(5)	43(3)	-23(3)	16(3)	-42(4)
C(60)	62(4)	66(4)	33(3)	-20(3)	11(3)	-25(3)
C(61)	28(3)	36(3)	32(2)	-13(2)	1(2)	-6(2)
C(62)	39(3)	40(3)	44(3)	-9(2)	4(2)	-8(2)
C(63)	41(4)	46(3)	67(4)	-12(3)	18(3)	-15(3)
C(64)	29(4)	74(5)	90(5)	-20(4)	16(3)	-12(3)
C(65)	42(5)	70(5)	101(6)	-10(4)	-14(4)	14(3)
C(66)	41(4)	51(3)	53(4)	-1(3)	-8(3)	-3(3)
C(67)	27(3)	23(2)	22(2)	1(2)	0(2)	0(2)
C(68)	24(2)	29(2)	24(2)	6(2)	-2(2)	1(2)
C(69)	29(3)	32(2)	25(2)	8(2)	5(2)	4(2)
C(70)	30(3)	34(2)	24(2)	-1(2)	2(2)	4(2)
C(71)	27(3)	39(3)	29(2)	9(2)	-1(2)	4(2)
C(72)	37(3)	52(3)	43(3)	6(2)	0(2)	-5(3)
C(73)	33(4)	79(5)	75(5)	8(4)	-3(3)	-18(3)
C(74)	26(3)	97(6)	55(4)	21(4)	14(3)	10(3)
C(75)	39(4)	69(4)	48(3)	18(3)	11(3)	12(3)
C(76)	38(3)	45(3)	35(3)	7(2)	6(2)	12(2)
C(77)	30(3)	36(3)	23(2)	8(2)	5(2)	3(2)
C(78)	38(3)	40(3)	38(3)	6(2)	-1(2)	4(2)

C(79)	38(3)	57(3)	34(3)	9(3)	-6(2)	14(3)
C(80)	40(3)	44(3)	42(3)	15(2)	6(2)	18(2)
C(81)	54(4)	39(3)	48(3)	8(2)	0(3)	8(3)
C(82)	43(3)	40(3)	34(3)	3(2)	-4(2)	3(2)
C(83)	33(3)	30(2)	34(2)	9(2)	-5(2)	5(2)
C(84)	49(4)	46(3)	43(3)	9(2)	3(3)	-1(3)
C(85)	37(4)	74(5)	67(4)	12(4)	15(3)	-17(3)
C(86)	28(4)	67(5)	108(6)	32(4)	-8(4)	-16(3)
C(87)	46(4)	67(4)	75(5)	14(4)	-26(3)	-23(3)
C(88)	39(4)	55(3)	41(3)	5(3)	-7(2)	-13(3)
C(1S)	86(9)	75(7)	146(13)	6(8)	-67(9)	-10(6)
C(2S)	21(3)	37(3)	53(4)	-13(3)	12(3)	-10(2)
C(3S)	41(6)	50(6)	14(4)	-7(4)	7(4)	-6(5)
C(4S)	180(20)	91(12)	20(7)	20(7)	-27(9)	-45(14)
C(5S)	74(8)	109(10)	76(7)	9(7)	5(6)	-11(7)
C(6S)	39(5)	70(5)	44(4)	19(4)	14(3)	6(4)
C(7SA)	16(6)	112(11)	63(7)	62(8)	17(5)	37(6)
C(7SB)	670(110)	27(11)	390(70)	-40(20)	500(80)	-50(30)
C(8SA)	140(30)	130(20)	220(40)	10(20)	-130(30)	6(18)
C(8SB)	81(19)	270(50)	75(14)	70(20)	18(13)	100(20)
C(3SB)	42(14)	48(14)	35(15)	11(10)	-14(10)	19(11)
C(4SB)	72(18)	54(15)	20(10)	4(10)	3(11)	8(13)
O(1)	20(2)	28(2)	25(2)	3(1)	-1(1)	0(1)
O(2)	26(2)	28(2)	27(2)	4(1)	-2(1)	1(1)
O(3)	29(2)	26(2)	23(2)	-1(1)	5(1)	-5(1)
O(4)	24(2)	29(2)	23(1)	-4(1)	1(1)	-2(1)
O(5)	20(2)	31(2)	24(1)	4(1)	-2(1)	4(1)
O(6)	23(2)	30(2)	27(2)	3(1)	3(1)	5(1)
O(7)	23(2)	24(2)	26(2)	-4(1)	0(1)	-1(1)
O(8)	25(2)	30(2)	28(2)	-7(1)	3(1)	-5(1)
O(1S)	22(2)	40(2)	22(2)	-10(2)	11(2)	-10(2)
O(2S)	8(2)	44(3)	31(2)	11(2)	5(2)	5(2)
Rh(1)	19(1)	22(1)	18(1)	0(1)	1(1)	0(1)
Rh(2)	19(1)	22(1)	18(1)	0(1)	1(1)	0(1)

Table 5. Hydrogen coordinates (x 10^4) and isotropic displacement parameters ($Å^2$x 10^3) for **3.19**.

	x	y	z	U(eq)
H(3A)	4191	7390	9088	46
H(3B)	4310	7088	8457	46
H(6A)	4997	7869	7888	74
H(7A)	5275	8060	6952	131
H(8A)	4370	8490	6367	133
H(9A)	3177	8567	6693	113
H(10A)	2884	8353	7607	84
H(12A)	3441	9144	8169	55
H(13A)	3425	10054	8685	66
H(14A)	3685	10027	9630	71
H(15A)	3992	9096	10040	76
H(16A)	4011	8170	9530	60
H(18A)	2170	8301	8822	41
H(19A)	1325	8333	9539	49
H(21A)	2137	6735	10164	53
H(22A)	3014	6708	9453	42
H(26A)	404	6748	6364	34
H(26B)	494	7110	5755	34
H(28A)	2398	8150	6136	44
H(29A)	3232	8357	5437	52
H(31A)	2495	6862	4591	59
H(32A)	1663	6646	5312	50
H(34A)	1217	8780	6818	59
H(35A)	1157	9768	6424	83
H(36A)	784	9877	5481	94
H(37A)	377	9016	5003	83
H(38A)	392	8022	5402	64
H(40A)	-525	7628	6843	47
H(41A)	-987	7743	7722	57
H(42A)	-171	7823	8490	62
H(43A)	1077	7861	8331	61
H(44A)	1552	7800	7421	43

H(47A)	1463	5031	5476	44
H(47B)	2262	5314	5705	44
H(50A)	2620	4061	7005	60
H(51)	3850	3846	7222	73
H(52A)	4756	3993	6560	96
H(53A)	4459	4309	5675	86
H(54A)	3248	4515	5451	67
H(56A)	2245	3218	6250	63
H(57A)	1617	2319	5962	80
H(58A)	578	2412	5380	89
H(59A)	170	3385	5134	74
H(60A)	768	4284	5423	64
H(62A)	877	4122	7011	49
H(63A)	-350	4050	7244	62
H(65A)	-780	5532	6262	85
H(66A)	438	5600	6021	58
H(70A)	2950	5567	9259	35
H(70B)	3789	5411	9500	35
H(72A)	4753	5975	8972	53
H(73A)	5999	6044	8681	75
H(75A)	5676	4545	7686	63
H(76A)	4458	4489	7971	47
H(78A)	4556	4752	9657	46
H(79A)	5350	3972	9989	52
H(80A)	5149	2940	9747	51
H(81A)	4203	2684	9113	56
H(82A)	3423	3460	8791	47
H(84A)	2200	4562	9643	55
H(85A)	1035	4186	9473	71
H(86A)	705	3831	8607	81
H(87A)	1589	3832	7872	75
H(88A)	2776	4226	8045	54
H(1SA)	-682	5645	7722	154
H(1SB)	-148	6184	7501	154
H(1SC)	-518	6240	8102	154
H(2S1)	129	5397	8392	44

H(2S2)	499	5341	7793	44
H(3SA)	318	6537	8786	42
H(3SB)	1183	6668	8802	42
H(4SA)	809	6161	9600	144
H(4SB)	1372	5733	9260	144
H(4SC)	508	5592	9237	144
H(5SA)	3855	6515	5402	129
H(5SB)	3340	6151	5834	129
H(5SC)	4159	5911	5716	129
H(6SA)	3802	7033	6224	61
H(6SB)	4624	6787	6110	61
H(7S1)	4990	5822	6490	76
H(7S2)	4637	5627	7074	76
H(7S3)	4411	6205	7289	436
H(7S4)	4679	6764	6907	436
H(8S1)	5724	6187	7218	242
H(8S2)	5042	6568	7465	242
H(8S3)	5393	6765	6882	242
H(8S4)	5681	5974	7018	214
H(8S5)	5490	6054	6373	214
H(8S6)	5182	5467	6709	214
H(3S1)	1048	5563	8998	50
H(3S2)	1518	6192	8957	50
H(4SD)	612	6320	9559	73
H(4SE)	18	6106	9107	73
H(4SF)	458	6744	9025	73

Table 6. Torsion angles [°] for **3.19**.

O(7)-C(1)-C(2)-C(17)	12.3(6)
O(8)-C(1)-C(2)-C(17)	-165.0(4)
O(7)-C(1)-C(2)-C(3)	156.4(4)
O(8)-C(1)-C(2)-C(3)	-20.9(6)
O(7)-C(1)-C(2)-C(4)	-137.2(4)
O(8)-C(1)-C(2)-C(4)	45.5(6)

C(17)-C(2)-C(3)-C(4)	-109.8(5)
C(1)-C(2)-C(3)-C(4)	109.3(5)
C(2)-C(3)-C(4)-C(5)	-107.0(5)
C(2)-C(3)-C(4)-C(11)	107.4(5)
C(17)-C(2)-C(4)-C(3)	109.3(5)
C(1)-C(2)-C(4)-C(3)	-103.9(5)
C(17)-C(2)-C(4)-C(5)	-142.7(5)
C(3)-C(2)-C(4)-C(5)	108.0(6)
C(1)-C(2)-C(4)-C(5)	4.1(7)
C(17)-C(2)-C(4)-C(11)	0.3(7)
C(3)-C(2)-C(4)-C(11)	-109.0(5)
C(1)-C(2)-C(4)-C(11)	147.1(5)
C(3)-C(4)-C(5)-C(6)	-49.5(7)
C(11)-C(4)-C(5)-C(6)	97.9(6)
C(2)-C(4)-C(5)-C(6)	-117.4(6)
C(3)-C(4)-C(5)-C(10)	134.2(6)
C(11)-C(4)-C(5)-C(10)	-78.3(7)
C(2)-C(4)-C(5)-C(10)	66.3(8)
C(10)-C(5)-C(6)-C(7)	-1.3(9)
C(4)-C(5)-C(6)-C(7)	-177.6(6)
C(5)-C(6)-C(7)-C(8)	3.6(12)
C(6)-C(7)-C(8)-C(9)	-4.8(14)
C(7)-C(8)-C(9)-C(10)	3.8(15)
C(8)-C(9)-C(10)-C(5)	-1.5(13)
C(6)-C(5)-C(10)-C(9)	0.2(10)
C(4)-C(5)-C(10)-C(9)	176.4(7)
C(3)-C(4)-C(11)-C(16)	-6.1(8)
C(5)-C(4)-C(11)-C(16)	-153.2(6)
C(2)-C(4)-C(11)-C(16)	62.5(8)
C(3)-C(4)-C(11)-C(12)	173.6(5)
C(5)-C(4)-C(11)-C(12)	26.5(8)
C(2)-C(4)-C(11)-C(12)	-117.8(6)
C(16)-C(11)-C(12)-C(13)	0.6(10)
C(4)-C(11)-C(12)-C(13)	-179.2(6)
C(11)-C(12)-C(13)-C(14)	-0.7(12)
C(12)-C(13)-C(14)-C(15)	0.8(13)

C(13)-C(14)-C(15)-C(16)	-0.9(13)
C(12)-C(11)-C(16)-C(15)	-0.6(10)
C(4)-C(11)-C(16)-C(15)	179.1(6)
C(14)-C(15)-C(16)-C(11)	0.8(12)
C(3)-C(2)-C(17)-C(22)	-56.8(6)
C(1)-C(2)-C(17)-C(22)	85.2(5)
C(4)-C(2)-C(17)-C(22)	-126.1(5)
C(3)-C(2)-C(17)-C(18)	125.7(5)
C(1)-C(2)-C(17)-C(18)	-92.4(6)
C(4)-C(2)-C(17)-C(18)	56.4(7)
C(22)-C(17)-C(18)-C(19)	-0.9(8)
C(2)-C(17)-C(18)-C(19)	176.7(5)
C(17)-C(18)-C(19)-C(20)	-0.5(9)
C(18)-C(19)-C(20)-C(21)	1.0(9)
C(18)-C(19)-C(20)-Br(3)	-179.9(5)
C(19)-C(20)-C(21)-C(22)	-0.1(9)
Br(3)-C(20)-C(21)-C(22)	-179.2(4)
C(18)-C(17)-C(22)-C(21)	1.7(8)
C(2)-C(17)-C(22)-C(21)	-175.9(5)
C(20)-C(21)-C(22)-C(17)	-1.2(9)
O(2)-C(23)-C(24)-C(26)	160.3(4)
O(1)-C(23)-C(24)-C(26)	-20.3(6)
O(2)-C(23)-C(24)-C(27)	16.3(6)
O(1)-C(23)-C(24)-C(27)	-164.3(4)
O(2)-C(23)-C(24)-C(25)	-131.1(5)
O(1)-C(23)-C(24)-C(25)	48.3(6)
C(23)-C(24)-C(25)-C(26)	-108.0(5)
C(27)-C(24)-C(25)-C(26)	106.8(5)
C(26)-C(24)-C(25)-C(33)	-112.4(5)
C(23)-C(24)-C(25)-C(33)	139.6(5)
C(27)-C(24)-C(25)-C(33)	-5.6(7)
C(26)-C(24)-C(25)-C(39)	102.9(5)
C(23)-C(24)-C(25)-C(39)	-5.1(7)
C(27)-C(24)-C(25)-C(39)	-150.3(5)
C(23)-C(24)-C(26)-C(25)	108.5(4)
C(27)-C(24)-C(26)-C(25)	-109.5(5)

C(33)-C(25)-C(26)-C(24)	105.1(5)
C(39)-C(25)-C(26)-C(24)	-111.5(4)
C(26)-C(24)-C(27)-C(28)	132.6(5)
C(23)-C(24)-C(27)-C(28)	-83.1(6)
C(25)-C(24)-C(27)-C(28)	64.1(7)
C(26)-C(24)-C(27)-C(32)	-51.0(7)
C(23)-C(24)-C(27)-C(32)	93.3(6)
C(25)-C(24)-C(27)-C(32)	-119.5(5)
C(32)-C(27)-C(28)-C(29)	-0.8(8)
C(24)-C(27)-C(28)-C(29)	175.7(5)
C(27)-C(28)-C(29)-C(30)	0.0(9)
C(28)-C(29)-C(30)-C(31)	1.5(9)
C(28)-C(29)-C(30)-Br(2)	-178.8(5)
C(29)-C(30)-C(31)-C(32)	-2.1(10)
Br(2)-C(30)-C(31)-C(32)	178.2(5)
C(30)-C(31)-C(32)-C(27)	1.2(10)
C(28)-C(27)-C(32)-C(31)	0.2(9)
C(24)-C(27)-C(32)-C(31)	-176.3(6)
C(26)-C(25)-C(33)-C(38)	6.5(8)
C(39)-C(25)-C(33)-C(38)	-137.7(6)
C(24)-C(25)-C(33)-C(38)	75.2(7)
C(26)-C(25)-C(33)-C(34)	-174.0(5)
C(39)-C(25)-C(33)-C(34)	41.8(7)
C(24)-C(25)-C(33)-C(34)	-105.3(6)
C(38)-C(33)-C(34)-C(35)	1.3(9)
C(25)-C(33)-C(34)-C(35)	-178.2(6)
C(33)-C(34)-C(35)-C(36)	-2.8(11)
C(34)-C(35)-C(36)-C(37)	3.1(12)
C(35)-C(36)-C(37)-C(38)	-1.9(12)
C(34)-C(33)-C(38)-C(37)	-0.1(9)
C(25)-C(33)-C(38)-C(37)	179.4(6)
C(36)-C(37)-C(38)-C(33)	0.4(11)
C(26)-C(25)-C(39)-C(44)	118.3(5)
C(33)-C(25)-C(39)-C(44)	-95.1(6)
C(24)-C(25)-C(39)-C(44)	51.1(7)
C(26)-C(25)-C(39)-C(40)	-63.3(6)

C(33)-C(25)-C(39)-C(40)	83.3(6)
C(24)-C(25)-C(39)-C(40)	-130.5(5)
C(44)-C(39)-C(40)-C(41)	1.6(8)
C(25)-C(39)-C(40)-C(41)	-176.8(5)
C(39)-C(40)-C(41)-C(42)	-3.0(9)
C(40)-C(41)-C(42)-C(43)	2.4(9)
C(41)-C(42)-C(43)-C(44)	-0.5(10)
C(40)-C(39)-C(44)-C(43)	0.3(8)
C(25)-C(39)-C(44)-C(43)	178.7(5)
C(42)-C(43)-C(44)-C(39)	-0.8(9)
O(4)-C(45)-C(46)-C(61)	-156.5(4)
O(3)-C(45)-C(46)-C(61)	20.8(6)
O(4)-C(45)-C(46)-C(47)	-12.3(7)
O(3)-C(45)-C(46)-C(47)	165.0(4)
O(4)-C(45)-C(46)-C(48)	54.5(6)
O(3)-C(45)-C(46)-C(48)	-128.2(5)
C(61)-C(46)-C(47)-C(48)	-109.0(5)
C(45)-C(46)-C(47)-C(48)	109.2(5)
C(46)-C(47)-C(48)-C(49)	-106.7(5)
C(46)-C(47)-C(48)-C(55)	106.7(6)
C(61)-C(46)-C(48)-C(49)	-144.9(5)
C(47)-C(46)-C(48)-C(49)	106.6(5)
C(45)-C(46)-C(48)-C(49)	2.0(7)
C(61)-C(46)-C(48)-C(47)	108.5(5)
C(45)-C(46)-C(48)-C(47)	-104.5(5)
C(61)-C(46)-C(48)-C(55)	-0.9(7)
C(47)-C(46)-C(48)-C(55)	-109.4(6)
C(45)-C(46)-C(48)-C(55)	146.0(5)
C(47)-C(48)-C(49)-C(50)	128.1(5)
C(55)-C(48)-C(49)-C(50)	-83.8(6)
C(46)-C(48)-C(49)-C(50)	61.2(7)
C(47)-C(48)-C(49)-C(54)	-52.1(7)
C(55)-C(48)-C(49)-C(54)	96.0(6)
C(46)-C(48)-C(49)-C(54)	-119.0(6)
C(54)-C(49)-C(50)-C(51)	-1.8(9)
C(48)-C(49)-C(50)-C(51)	178.0(6)

C(49)-C(50)-C(51)-C(52)	1.7(10)
C(50)-C(51)-C(52)-C(53)	-1.2(12)
C(51)-C(52)-C(53)-C(54)	0.9(13)
C(52)-C(53)-C(54)-C(49)	-1.1(12)
C(50)-C(49)-C(54)-C(53)	1.6(9)
C(48)-C(49)-C(54)-C(53)	-178.2(6)
C(49)-C(48)-C(55)-C(56)	20.0(7)
C(47)-C(48)-C(55)-C(56)	167.2(5)
C(46)-C(48)-C(55)-C(56)	-124.6(6)
C(49)-C(48)-C(55)-C(60)	-158.2(5)
C(47)-C(48)-C(55)-C(60)	-11.1(8)
C(46)-C(48)-C(55)-C(60)	57.1(7)
C(60)-C(55)-C(56)-C(57)	0.8(9)
C(48)-C(55)-C(56)-C(57)	-177.5(6)
C(55)-C(56)-C(57)-C(58)	0.5(10)
C(56)-C(57)-C(58)-C(59)	-1.3(10)
C(57)-C(58)-C(59)-C(60)	0.8(10)
C(58)-C(59)-C(60)-C(55)	0.5(9)
C(56)-C(55)-C(60)-C(59)	-1.3(8)
C(48)-C(55)-C(60)-C(59)	177.0(5)
C(47)-C(46)-C(61)-C(66)	-49.6(7)
C(45)-C(46)-C(61)-C(66)	93.2(6)
C(48)-C(46)-C(61)-C(66)	-118.2(6)
C(47)-C(46)-C(61)-C(62)	136.2(5)
C(45)-C(46)-C(61)-C(62)	-81.0(6)
C(48)-C(46)-C(61)-C(62)	67.6(6)
C(66)-C(61)-C(62)-C(63)	1.6(8)
C(46)-C(61)-C(62)-C(63)	176.0(5)
C(61)-C(62)-C(63)-C(64)	0.2(10)
C(62)-C(63)-C(64)-C(65)	-2.4(11)
C(62)-C(63)-C(64)-Br(1)	178.9(5)
C(63)-C(64)-C(65)-C(66)	2.8(13)
Br(1)-C(64)-C(65)-C(66)	-178.6(6)
C(64)-C(65)-C(66)-C(61)	-0.9(12)
C(62)-C(61)-C(66)-C(65)	-1.2(9)
C(46)-C(61)-C(66)-C(65)	-175.7(6)

O(6)-C(67)-C(68)-C(71)	16.4(6)
O(5)-C(67)-C(68)-C(71)	-161.2(4)
O(6)-C(67)-C(68)-C(70)	161.7(4)
O(5)-C(67)-C(68)-C(70)	-15.9(6)
O(6)-C(67)-C(68)-C(69)	-132.2(4)
O(5)-C(67)-C(68)-C(69)	50.2(6)
C(71)-C(68)-C(69)-C(83)	-144.3(5)
C(70)-C(68)-C(69)-C(83)	105.7(5)
C(67)-C(68)-C(69)-C(83)	2.0(6)
C(71)-C(68)-C(69)-C(70)	110.0(5)
C(67)-C(68)-C(69)-C(70)	-103.7(5)
C(71)-C(68)-C(69)-C(77)	1.2(7)
C(70)-C(68)-C(69)-C(77)	-108.7(5)
C(67)-C(68)-C(69)-C(77)	147.6(4)
C(71)-C(68)-C(70)-C(69)	-109.0(5)
C(67)-C(68)-C(70)-C(69)	108.5(5)
C(83)-C(69)-C(70)-C(68)	-109.5(5)
C(77)-C(69)-C(70)-C(68)	105.3(5)
C(70)-C(68)-C(71)-C(72)	-42.4(7)
C(67)-C(68)-C(71)-C(72)	100.6(6)
C(69)-C(68)-C(71)-C(72)	-111.8(6)
C(70)-C(68)-C(71)-C(76)	140.5(5)
C(67)-C(68)-C(71)-C(76)	-76.5(6)
C(69)-C(68)-C(71)-C(76)	71.1(6)
C(76)-C(71)-C(72)-C(73)	2.3(9)
C(68)-C(71)-C(72)-C(73)	-174.9(6)
C(71)-C(72)-C(73)-C(74)	-1.2(10)
C(72)-C(73)-C(74)-C(75)	-0.1(11)
C(72)-C(73)-C(74)-Br(4)	179.3(5)
C(73)-C(74)-C(75)-C(76)	0.3(11)
Br(4)-C(74)-C(75)-C(76)	-179.1(5)
C(74)-C(75)-C(76)-C(71)	0.8(9)
C(72)-C(71)-C(76)-C(75)	-2.1(8)
C(68)-C(71)-C(76)-C(75)	175.2(5)
C(83)-C(69)-C(77)-C(78)	-150.4(5)
C(70)-C(69)-C(77)-C(78)	-4.5(7)

C(68)-C(69)-C(77)-C(78)	62.5(6)
C(83)-C(69)-C(77)-C(82)	27.3(7)
C(70)-C(69)-C(77)-C(82)	173.2(5)
C(68)-C(69)-C(77)-C(82)	-119.8(5)
C(82)-C(77)-C(78)-C(79)	-0.7(8)
C(69)-C(77)-C(78)-C(79)	177.1(5)
C(77)-C(78)-C(79)-C(80)	-0.8(9)
C(78)-C(79)-C(80)-C(81)	2.4(9)
C(79)-C(80)-C(81)-C(82)	-2.4(9)
C(80)-C(81)-C(82)-C(77)	0.9(9)
C(78)-C(77)-C(82)-C(81)	0.6(8)
C(69)-C(77)-C(82)-C(81)	-177.2(5)
C(70)-C(69)-C(83)-C(84)	-57.5(6)
C(77)-C(69)-C(83)-C(84)	88.9(6)
C(68)-C(69)-C(83)-C(84)	-125.0(5)
C(70)-C(69)-C(83)-C(88)	123.3(5)
C(77)-C(69)-C(83)-C(88)	-90.4(6)
C(68)-C(69)-C(83)-C(88)	55.7(7)
C(88)-C(83)-C(84)-C(85)	-0.2(9)
C(69)-C(83)-C(84)-C(85)	-179.5(6)
C(83)-C(84)-C(85)-C(86)	0.0(11)
C(84)-C(85)-C(86)-C(87)	0.6(12)
C(85)-C(86)-C(87)-C(88)	-0.9(12)
C(86)-C(87)-C(88)-C(83)	0.7(11)
C(84)-C(83)-C(88)-C(87)	-0.1(9)
C(69)-C(83)-C(88)-C(87)	179.2(6)
C(5S)-C(6S)-C(7SB)-O(2S)	-55(2)
C(5S)-C(6S)-C(7SB)-C(8SB)	63(4)
O(2S)-C(6S)-C(7SB)-C(8SB)	118(3)
O(2)-C(23)-O(1)-Rh(1)	3.5(6)
C(24)-C(23)-O(1)-Rh(1)	-175.8(3)
O(1)-C(23)-O(2)-Rh(2)	14.5(6)
C(24)-C(23)-O(2)-Rh(2)	-166.2(3)
O(4)-C(45)-O(3)-Rh(1)	25.1(6)
C(46)-C(45)-O(3)-Rh(1)	-152.0(3)
O(3)-C(45)-O(4)-Rh(2)	-9.2(6)

C(46)-C(45)-O(4)-Rh(2)	167.7(3)
O(6)-C(67)-O(5)-Rh(1)	-4.2(6)
C(68)-C(67)-O(5)-Rh(1)	173.1(3)
O(5)-C(67)-O(6)-Rh(2)	20.4(6)
C(68)-C(67)-O(6)-Rh(2)	-157.0(3)
O(8)-C(1)-O(7)-Rh(1)	20.8(6)
C(2)-C(1)-O(7)-Rh(1)	-156.2(3)
O(7)-C(1)-O(8)-Rh(2)	-5.2(6)
C(2)-C(1)-O(8)-Rh(2)	171.8(3)
C(1S)-C(2S)-O(1S)-C(3S)	80.1(12)
C(1S)-C(2S)-O(1S)-C(3SB)	117.0(15)
C(1S)-C(2S)-O(1S)-Rh(1)	-102.8(10)
C(4S)-C(3S)-O(1S)-C(2S)	72.8(15)
C(4S)-C(3S)-O(1S)-C(3SB)	-20(2)
C(4S)-C(3S)-O(1S)-Rh(1)	-104.2(12)
C(4SB)-C(3SB)-O(1S)-C(2S)	-74(2)
C(4SB)-C(3SB)-O(1S)-C(3S)	30.3(18)
C(4SB)-C(3SB)-O(1S)-Rh(1)	143.7(19)
C(8SB)-C(7SB)-O(2S)-C(7SA)	23.4(18)
C(6S)-C(7SB)-O(2S)-C(7SA)	103(2)
C(8SB)-C(7SB)-O(2S)-C(6S)	-80(3)
C(8SB)-C(7SB)-O(2S)-Rh(2)	136(2)
C(6S)-C(7SB)-O(2S)-Rh(2)	-144.1(17)
C(8SA)-C(7SA)-O(2S)-C(7SB)	-12(4)
C(8SA)-C(7SA)-O(2S)-C(6S)	80(2)
C(8SA)-C(7SA)-O(2S)-Rh(2)	-98(2)
C(5S)-C(6S)-O(2S)-C(7SB)	134.6(19)
C(5S)-C(6S)-O(2S)-C(7SA)	96.9(13)
C(7SB)-C(6S)-O(2S)-C(7SA)	-37.6(16)
C(5S)-C(6S)-O(2S)-Rh(2)	-84.6(9)
C(7SB)-C(6S)-O(2S)-Rh(2)	141(2)
C(67)-O(5)-Rh(1)-O(3)	77.2(3)
C(67)-O(5)-Rh(1)-O(7)	-98.7(3)
C(67)-O(5)-Rh(1)-O(1)	-3.3(14)
C(67)-O(5)-Rh(1)-O(1S)	170.5(3)
C(67)-O(5)-Rh(1)-Rh(2)	-10.4(3)

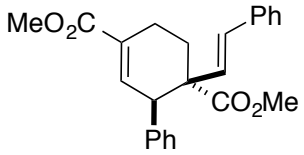
C(45)-O(3)-Rh(1)-O(5)	-110.0(3)
C(45)-O(3)-Rh(1)-O(7)	-21(2)
C(45)-O(3)-Rh(1)-O(1)	64.0(3)
C(45)-O(3)-Rh(1)-O(1S)	157.6(3)
C(45)-O(3)-Rh(1)-Rh(2)	-23.2(3)
C(1)-O(7)-Rh(1)-O(5)	65.7(3)
C(1)-O(7)-Rh(1)-O(3)	-24(2)
C(1)-O(7)-Rh(1)-O(1)	-108.3(3)
C(1)-O(7)-Rh(1)-O(1S)	157.7(3)
C(1)-O(7)-Rh(1)-Rh(2)	-21.4(3)
C(23)-O(1)-Rh(1)-O(5)	-22.3(14)
C(23)-O(1)-Rh(1)-O(3)	-103.4(3)
C(23)-O(1)-Rh(1)-O(7)	72.5(3)
C(23)-O(1)-Rh(1)-O(1S)	163.9(3)
C(23)-O(1)-Rh(1)-Rh(2)	-15.2(3)
C(2S)-O(1S)-Rh(1)-O(5)	-111.4(5)
C(3S)-O(1S)-Rh(1)-O(5)	65.5(7)
C(3SB)-O(1S)-Rh(1)-O(5)	28.7(12)
C(2S)-O(1S)-Rh(1)-O(3)	-16.3(5)
C(3S)-O(1S)-Rh(1)-O(3)	160.6(7)
C(3SB)-O(1S)-Rh(1)-O(3)	123.8(12)
C(2S)-O(1S)-Rh(1)-O(7)	163.5(5)
C(3S)-O(1S)-Rh(1)-O(7)	-19.5(7)
C(3SB)-O(1S)-Rh(1)-O(7)	-56.3(12)
C(2S)-O(1S)-Rh(1)-O(1)	67.9(5)
C(3S)-O(1S)-Rh(1)-O(1)	-115.1(7)
C(3SB)-O(1S)-Rh(1)-O(1)	-152.0(12)
C(2S)-O(1S)-Rh(1)-Rh(2)	-155(5)
C(3S)-O(1S)-Rh(1)-Rh(2)	22(5)
C(3SB)-O(1S)-Rh(1)-Rh(2)	-15(5)
C(23)-O(2)-Rh(2)-O(6)	-32(2)
C(23)-O(2)-Rh(2)-O(4)	67.2(3)
C(23)-O(2)-Rh(2)-O(8)	-107.5(3)
C(23)-O(2)-Rh(2)-O(2S)	159.3(3)
C(23)-O(2)-Rh(2)-Rh(1)	-20.3(3)
C(67)-O(6)-Rh(2)-O(2)	-10(2)

C(67)-O(6)-Rh(2)-O(4)	-108.7(3)
C(67)-O(6)-Rh(2)-O(8)	65.9(3)
C(67)-O(6)-Rh(2)-O(2S)	158.9(3)
C(67)-O(6)-Rh(2)-Rh(1)	-21.6(3)
C(45)-O(4)-Rh(2)-O(2)	-96.4(3)
C(45)-O(4)-Rh(2)-O(6)	79.4(3)
C(45)-O(4)-Rh(2)-O(8)	-14.6(16)
C(45)-O(4)-Rh(2)-O(2S)	172.1(3)
C(45)-O(4)-Rh(2)-Rh(1)	-8.2(3)
C(1)-O(8)-Rh(2)-O(2)	78.1(3)
C(1)-O(8)-Rh(2)-O(6)	-97.8(3)
C(1)-O(8)-Rh(2)-O(4)	-3.4(16)
C(1)-O(8)-Rh(2)-O(2S)	170.0(3)
C(1)-O(8)-Rh(2)-Rh(1)	-9.7(3)
C(7SB)-O(2S)-Rh(2)-O(2)	133.9(19)
C(7SA)-O(2S)-Rh(2)-O(2)	172.4(10)
C(6S)-O(2S)-Rh(2)-O(2)	-6.0(6)
C(7SB)-O(2S)-Rh(2)-O(6)	-45.3(19)
C(7SA)-O(2S)-Rh(2)-O(6)	-6.8(10)
C(6S)-O(2S)-Rh(2)-O(6)	174.8(6)
C(7SB)-O(2S)-Rh(2)-O(4)	-140.4(19)
C(7SA)-O(2S)-Rh(2)-O(4)	-101.9(10)
C(6S)-O(2S)-Rh(2)-O(4)	79.7(6)
C(7SB)-O(2S)-Rh(2)-O(8)	40(2)
C(7SA)-O(2S)-Rh(2)-O(8)	78.7(10)
C(6S)-O(2S)-Rh(2)-O(8)	-99.7(6)
C(7SB)-O(2S)-Rh(2)-Rh(1)	-175(100)
C(7SA)-O(2S)-Rh(2)-Rh(1)	-137(16)
C(6S)-O(2S)-Rh(2)-Rh(1)	45(17)
O(5)-Rh(1)-Rh(2)-O(2)	-165.48(13)
O(3)-Rh(1)-Rh(2)-O(2)	99.43(13)
O(7)-Rh(1)-Rh(2)-O(2)	-80.39(13)
O(1)-Rh(1)-Rh(2)-O(2)	15.27(13)
O(1S)-Rh(1)-Rh(2)-O(2)	-122(5)
O(5)-Rh(1)-Rh(2)-O(6)	13.69(13)
O(3)-Rh(1)-Rh(2)-O(6)	-81.40(13)

O(7)-Rh(1)-Rh(2)-O(6)	98.77(13)
O(1)-Rh(1)-Rh(2)-O(6)	-165.57(13)
O(1S)-Rh(1)-Rh(2)-O(6)	57(5)
O(5)-Rh(1)-Rh(2)-O(4)	108.86(14)
O(3)-Rh(1)-Rh(2)-O(4)	13.76(13)
O(7)-Rh(1)-Rh(2)-O(4)	-166.06(13)
O(1)-Rh(1)-Rh(2)-O(4)	-70.40(13)
O(1S)-Rh(1)-Rh(2)-O(4)	152(5)
O(5)-Rh(1)-Rh(2)-O(8)	-71.74(14)
O(3)-Rh(1)-Rh(2)-O(8)	-166.83(13)
O(7)-Rh(1)-Rh(2)-O(8)	13.34(13)
O(1)-Rh(1)-Rh(2)-O(8)	109.00(13)
O(1S)-Rh(1)-Rh(2)-O(8)	-28(5)
O(5)-Rh(1)-Rh(2)-O(2S)	144(17)
O(3)-Rh(1)-Rh(2)-O(2S)	49(17)
O(7)-Rh(1)-Rh(2)-O(2S)	-131(17)
O(1)-Rh(1)-Rh(2)-O(2S)	-35(17)
O(1S)-Rh(1)-Rh(2)-O(2S)	-173(100)

Symmetry transformations used to generate equivalent atoms:

2: X-ray crystallographic structure of 4.15



4.15

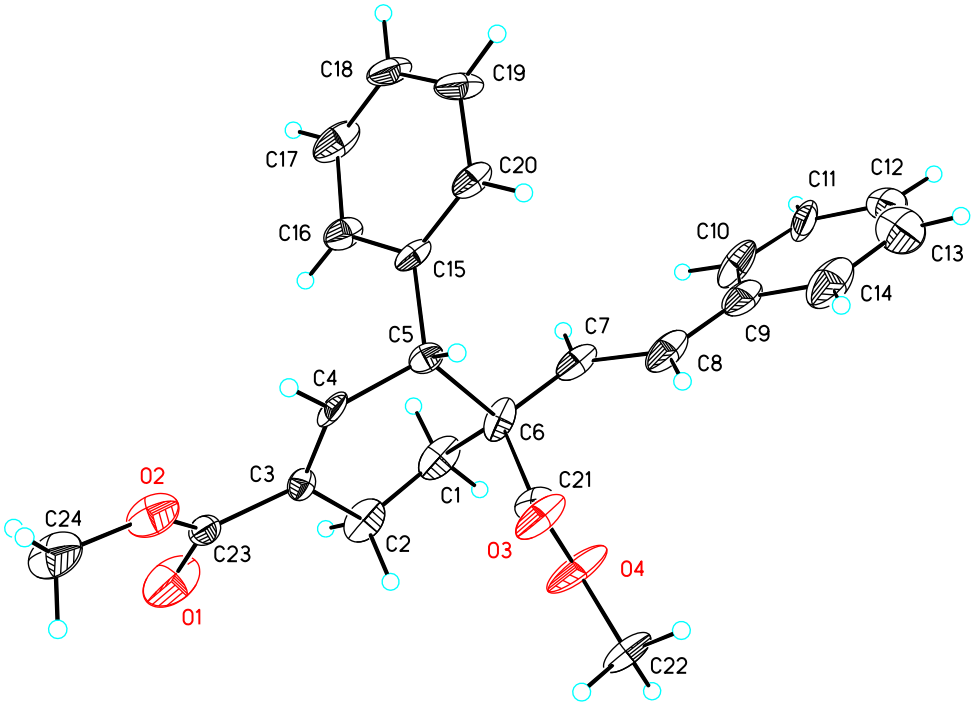


Table 1. Crystal data and structure refinement for **4.15**.

Identification code	qin_4_133	
Empirical formula	C24 H24 O4	
Formula weight	376.43	
Temperature	173(2) K	
Wavelength	1.54178 Å	
Crystal system	Triclinic	
Space group	P-1	
Unit cell dimensions	a = 9.2295(3) Å	á= 86.591(2)°.
	b = 10.3951(4) Å	â= 69.851(2)°.
	c = 11.3783(5) Å	ã = 79.622(2)°.
Volume	1008.07(7) Å^3	
Z	2	
Density (calculated)	1.240 Mg/m^3	
Absorption coefficient	0.672 mm^{-1}	
F(000)	400	
Crystal size	0.45 x 0.26 x 0.13 mm^3	
Theta range for data collection	4.14 to 69.41°.	

Index ranges	-11<=h<=11, -12<=k<=12, -13<=l<=13
Reflections collected	6798
Independent reflections	3018 [R(int) = 0.0115]
Completeness to theta = 69.41°	79.7 %
Absorption correction	Semi-empirical from equivalents
Max. and min. transmission	0.9177 and 0.7518
Refinement method	Full-matrix least-squares on F^2
Data / restraints / parameters	3018 / 0 / 253
Goodness-of-fit on F^2	1.009
Final R indices [I>2sigma(I)]	R1 = 0.1114, wR2 = 0.2482
R indices (all data)	R1 = 0.1686, wR2 = 0.3947
Largest diff. peak and hole	1.170 and -0.883 e.Å^{-3}

Table 2. Atomic coordinates (x 10^4) and equivalent isotropic displacement parameters ($Å^2$x 10^3) for **4.15**. U(eq) is defined as one third of the trace of the orthogonalized U^{ij} tensor.

	x	y	z	U(eq)
C(1)	11428(8)	252(7)	861(6)	25(2)
C(2)	12495(8)	1272(7)	566(6)	27(2)
C(3)	11756(7)	2460(6)	1385(6)	19(1)
C(4)	10483(7)	2491(6)	2420(6)	20(1)
C(5)	9653(7)	1358(6)	2889(6)	17(1)
C(6)	10670(8)	21(6)	2289(6)	23(2)
C(7)	9745(8)	-1050(7)	2489(7)	28(2)
C(8)	9519(8)	-1906(7)	3426(6)	29(2)
C(9)	8652(8)	-2994(7)	3598(7)	29(2)
C(10)	8123(9)	-3388(7)	2709(8)	36(2)
C(11)	7301(9)	-4426(8)	2899(9)	40(2)
C(12)	6996(9)	-5077(7)	4056(9)	43(2)
C(13)	7490(12)	-4710(9)	4909(8)	50(2)
C(14)	8358(10)	-3679(9)	4744(8)	42(2)
C(15)	8027(7)	1591(6)	2818(6)	20(1)
C(16)	7677(8)	2218(7)	1774(6)	25(1)
C(17)	6203(9)	2456(8)	1744(7)	33(2)
C(18)	4974(8)	2027(8)	2695(7)	33(2)
C(19)	5297(8)	1407(7)	3741(7)	28(2)
C(20)	6786(8)	1180(6)	3758(6)	24(1)
C(21)	11948(7)	-351(6)	2874(6)	19(1)
C(22)	14317(8)	-1792(8)	2684(7)	33(2)
C(23)	12501(7)	3647(7)	979(6)	23(1)
C(24)	12695(11)	5733(8)	1527(9)	46(2)
O(1)	11963(6)	57(5)	3830(4)	32(1)
O(2)	13094(6)	-1287(5)	2175(5)	34(1)
O(3)	13446(7)	3754(6)	-46(5)	46(2)
O(4)	12059(6)	4556(5)	1855(5)	34(1)

Table 3. Bond lengths [Å] and angles [°] for **4.15**.

C(1)-C(2)	1.520(10)
C(1)-C(6)	1.555(9)
C(1)-H(1A)	0.9900
C(1)-H(1B)	0.9900
C(2)-C(3)	1.502(9)
C(2)-H(2A)	0.9900
C(2)-H(2B)	0.9900
C(3)-C(4)	1.344(9)
C(3)-C(23)	1.492(9)
C(4)-C(5)	1.492(8)
C(4)-H(4A)	0.9500
C(5)-C(15)	1.506(8)
C(5)-C(6)	1.575(8)
C(5)-H(5A)	1.0000
C(6)-C(7)	1.483(10)
C(6)-C(21)	1.526(8)
C(7)-C(8)	1.331(11)
C(7)-H(7A)	0.9500
C(8)-C(9)	1.467(11)
C(8)-H(8A)	0.9500
C(9)-C(10)	1.374(11)
C(9)-C(14)	1.414(12)
C(10)-C(11)	1.393(12)
C(10)-H(10A)	0.9500
C(11)-C(12)	1.406(13)
C(11)-H(11A)	0.9500
C(12)-C(13)	1.307(14)
C(12)-H(12A)	0.9500
C(13)-C(14)	1.417(13)
C(13)-H(13A)	0.9500
C(14)-H(14A)	0.9500
C(15)-C(20)	1.385(10)
C(15)-C(16)	1.427(9)
C(16)-C(17)	1.350(10)
C(16)-H(16A)	0.9500
C(17)-C(18)	1.391(11)

C(17)-H(17A)	0.9500
C(18)-C(19)	1.416(10)
C(18)-H(18A)	0.9500
C(19)-C(20)	1.358(9)
C(19)-H(19A)	0.9500
C(20)-H(20A)	0.9500
C(21)-O(1)	1.196(8)
C(21)-O(2)	1.356(7)
C(22)-O(2)	1.444(8)
C(22)-H(22A)	0.9800
C(22)-H(22B)	0.9800
C(22)-H(22C)	0.9800
C(23)-O(3)	1.205(9)
C(23)-O(4)	1.321(8)
C(24)-O(4)	1.426(10)
C(24)-H(24A)	0.9800
C(24)-H(24B)	0.9800
C(24)-H(24C)	0.9800

C(2)-C(1)-C(6)	113.1(5)
C(2)-C(1)-H(1A)	109.0
C(6)-C(1)-H(1A)	109.0
C(2)-C(1)-H(1B)	109.0
C(6)-C(1)-H(1B)	109.0
H(1A)-C(1)-H(1B)	107.8
C(3)-C(2)-C(1)	111.7(5)
C(3)-C(2)-H(2A)	109.3
C(1)-C(2)-H(2A)	109.3
C(3)-C(2)-H(2B)	109.3
C(1)-C(2)-H(2B)	109.3
H(2A)-C(2)-H(2B)	107.9
C(4)-C(3)-C(23)	120.5(6)
C(4)-C(3)-C(2)	123.2(6)
C(23)-C(3)-C(2)	116.3(6)
C(3)-C(4)-C(5)	124.2(6)
C(3)-C(4)-H(4A)	117.9

C(5)-C(4)-H(4A)	117.9
C(4)-C(5)-C(15)	112.6(5)
C(4)-C(5)-C(6)	112.6(5)
C(15)-C(5)-C(6)	113.6(5)
C(4)-C(5)-H(5A)	105.7
C(15)-C(5)-H(5A)	105.7
C(6)-C(5)-H(5A)	105.7
C(7)-C(6)-C(21)	109.5(5)
C(7)-C(6)-C(1)	109.5(5)
C(21)-C(6)-C(1)	109.7(5)
C(7)-C(6)-C(5)	113.1(5)
C(21)-C(6)-C(5)	107.6(5)
C(1)-C(6)-C(5)	107.4(5)
C(8)-C(7)-C(6)	126.6(6)
C(8)-C(7)-H(7A)	116.7
C(6)-C(7)-H(7A)	116.7
C(7)-C(8)-C(9)	126.5(7)
C(7)-C(8)-H(8A)	116.7
C(9)-C(8)-H(8A)	116.7
C(10)-C(9)-C(14)	118.5(8)
C(10)-C(9)-C(8)	123.9(7)
C(14)-C(9)-C(8)	117.6(7)
C(9)-C(10)-C(11)	122.7(8)
C(9)-C(10)-H(10A)	118.7
C(11)-C(10)-H(10A)	118.7
C(10)-C(11)-C(12)	117.9(8)
C(10)-C(11)-H(11A)	121.1
C(12)-C(11)-H(11A)	121.1
C(13)-C(12)-C(11)	120.0(8)
C(13)-C(12)-H(12A)	120.0
C(11)-C(12)-H(12A)	120.0
C(12)-C(13)-C(14)	123.9(9)
C(12)-C(13)-H(13A)	118.1
C(14)-C(13)-H(13A)	118.1
C(9)-C(14)-C(13)	117.0(8)
C(9)-C(14)-H(14A)	121.5

C(13)-C(14)-H(14A)	121.5
C(20)-C(15)-C(16)	116.1(6)
C(20)-C(15)-C(5)	121.5(6)
C(16)-C(15)-C(5)	122.4(6)
C(17)-C(16)-C(15)	121.5(6)
C(17)-C(16)-H(16A)	119.2
C(15)-C(16)-H(16A)	119.2
C(16)-C(17)-C(18)	121.4(7)
C(16)-C(17)-H(17A)	119.3
C(18)-C(17)-H(17A)	119.3
C(17)-C(18)-C(19)	117.8(6)
C(17)-C(18)-H(18A)	121.1
C(19)-C(18)-H(18A)	121.1
C(20)-C(19)-C(18)	119.9(7)
C(20)-C(19)-H(19A)	120.0
C(18)-C(19)-H(19A)	120.0
C(19)-C(20)-C(15)	123.1(6)
C(19)-C(20)-H(20A)	118.5
C(15)-C(20)-H(20A)	118.5
O(1)-C(21)-O(2)	122.6(6)
O(1)-C(21)-C(6)	127.1(5)
O(2)-C(21)-C(6)	110.2(5)
O(2)-C(22)-H(22A)	109.5
O(2)-C(22)-H(22B)	109.5
H(22A)-C(22)-H(22B)	109.5
O(2)-C(22)-H(22C)	109.5
H(22A)-C(22)-H(22C)	109.5
H(22B)-C(22)-H(22C)	109.5
O(3)-C(23)-O(4)	123.0(7)
O(3)-C(23)-C(3)	123.0(6)
O(4)-C(23)-C(3)	114.0(6)
O(4)-C(24)-H(24A)	109.5
O(4)-C(24)-H(24B)	109.5
H(24A)-C(24)-H(24B)	109.5
O(4)-C(24)-H(24C)	109.5
H(24A)-C(24)-H(24C)	109.5

H(24B)-C(24)-H(24C)	109.5
C(21)-O(2)-C(22)	115.4(5)
C(23)-O(4)-C(24)	117.2(6)

Symmetry transformations used to generate equivalent atoms:

Table 4. Anisotropic displacement parameters ($Å^2 x\ 10^3$) for **4.15**. The anisotropic displacement factor exponent takes the form: $-2ð^2[\ h^2\ a^{*2}U^{11} + ...\ + 2\ h\ k\ a^*\ b^*\ U^{12}\ ]$

	U^{11}	U^{22}	U^{33}	U^{23}	U^{13}	U^{12}
C(1)	30(3)	26(3)	16(3)	-6(3)	-8(2)	2(3)
C(2)	29(3)	32(4)	17(3)	-7(3)	-6(3)	3(3)
C(3)	17(3)	18(3)	22(3)	1(3)	-9(2)	-2(2)
C(4)	16(3)	17(3)	24(3)	3(3)	-6(2)	0(2)
C(5)	20(3)	14(3)	18(3)	-3(2)	-6(2)	-1(2)
C(6)	29(3)	20(3)	18(3)	-10(3)	-12(3)	9(3)
C(7)	25(3)	26(3)	31(4)	-4(3)	-13(3)	6(3)
C(8)	29(4)	31(4)	23(3)	-3(3)	-7(3)	2(3)
C(9)	22(3)	26(3)	36(4)	-4(3)	-8(3)	5(3)
C(10)	42(4)	24(4)	48(5)	2(4)	-26(4)	0(3)
C(11)	33(4)	28(4)	63(5)	-3(4)	-23(4)	0(3)
C(12)	27(4)	22(4)	64(6)	1(4)	4(4)	-5(3)
C(13)	60(6)	40(5)	36(4)	6(4)	4(4)	-15(4)
C(14)	46(5)	39(4)	35(4)	-1(4)	-5(3)	-7(4)
C(15)	20(3)	21(3)	19(3)	-3(3)	-9(2)	5(2)
C(16)	25(3)	32(4)	16(3)	10(3)	-6(2)	-3(3)
C(17)	35(4)	40(4)	26(3)	6(3)	-18(3)	1(3)
C(18)	20(3)	40(4)	39(4)	7(4)	-14(3)	-1(3)
C(19)	20(3)	34(4)	30(4)	6(3)	-9(3)	-8(3)
C(20)	25(3)	22(3)	24(3)	3(3)	-9(3)	0(2)
C(21)	15(3)	18(3)	23(3)	-6(3)	-7(2)	0(2)
C(22)	25(3)	35(4)	42(4)	-13(3)	-20(3)	12(3)
C(23)	16(3)	26(3)	26(3)	2(3)	-6(2)	-1(2)
C(24)	45(5)	31(4)	50(5)	-3(4)	-2(4)	-4(3)
O(1)	31(3)	37(3)	23(2)	-6(2)	-14(2)	13(2)
O(2)	31(3)	32(3)	32(3)	-12(2)	-13(2)	19(2)
O(3)	49(3)	42(3)	32(3)	6(3)	7(2)	-12(3)
O(4)	32(3)	23(3)	40(3)	-7(2)	-4(2)	-4(2)

Table 5. Hydrogen coordinates (x 10^4) and isotropic displacement parameters ($Å^2$x 10^3) for QIN_4_133.

	x	y	z	U(eq)
H(1A)	12041	-585	456	30
H(1B)	10587	537	500	30
H(2A)	13494	884	687	33
H(2B)	12732	1534	-323	33
H(4A)	10085	3285	2883	24
H(5A)	9511	1288	3801	21
H(7A)	9264	-1134	1888	33
H(8A)	9965	-1801	4045	35
H(10A)	8327	-2935	1935	43
H(11A)	6957	-4686	2266	48
H(12A)	6430	-5784	4217	52
H(13A)	7254	-5161	5685	60
H(14A)	8727	-3458	5377	51
H(16A)	8501	2475	1084	30
H(17A)	6001	2925	1059	40
H(18A)	3952	2147	2644	39
H(19A)	4473	1149	4430	33
H(20A)	6985	717	4447	29
H(22A)	15089	-2456	2116	50
H(22B)	13861	-2186	3503	50
H(22C)	14830	-1077	2778	50
H(24A)	12285	6324	2251	69
H(24B)	12397	6156	832	69
H(24C)	13839	5528	1274	69

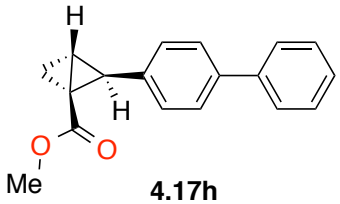
Table 6. Torsion angles [°] for **4.15**.

C(6)-C(1)-C(2)-C(3)	-45.3(7)
C(1)-C(2)-C(3)-C(4)	13.7(9)
C(1)-C(2)-C(3)-C(23)	-165.3(5)
C(23)-C(3)-C(4)-C(5)	179.4(5)
C(2)-C(3)-C(4)-C(5)	0.4(10)
C(3)-C(4)-C(5)-C(15)	-113.6(7)
C(3)-C(4)-C(5)-C(6)	16.4(8)
C(2)-C(1)-C(6)-C(7)	-176.0(5)
C(2)-C(1)-C(6)-C(21)	-55.8(7)
C(2)-C(1)-C(6)-C(5)	60.9(7)
C(4)-C(5)-C(6)-C(7)	-165.5(5)
C(15)-C(5)-C(6)-C(7)	-36.0(8)
C(4)-C(5)-C(6)-C(21)	73.4(7)
C(15)-C(5)-C(6)-C(21)	-157.1(5)
C(4)-C(5)-C(6)-C(1)	-44.6(7)
C(15)-C(5)-C(6)-C(1)	84.9(7)
C(21)-C(6)-C(7)-C(8)	27.6(9)
C(1)-C(6)-C(7)-C(8)	147.9(7)
C(5)-C(6)-C(7)-C(8)	-92.5(8)
C(6)-C(7)-C(8)-C(9)	-177.6(6)
C(7)-C(8)-C(9)-C(10)	9.3(11)
C(7)-C(8)-C(9)-C(14)	-171.3(7)
C(14)-C(9)-C(10)-C(11)	0.6(11)
C(8)-C(9)-C(10)-C(11)	-180.0(7)
C(9)-C(10)-C(11)-C(12)	0.7(11)
C(10)-C(11)-C(12)-C(13)	-0.6(12)
C(11)-C(12)-C(13)-C(14)	-0.8(14)
C(10)-C(9)-C(14)-C(13)	-1.8(11)
C(8)-C(9)-C(14)-C(13)	178.7(7)
C(12)-C(13)-C(14)-C(9)	2.0(14)
C(4)-C(5)-C(15)-C(20)	-140.7(6)
C(6)-C(5)-C(15)-C(20)	89.8(7)
C(4)-C(5)-C(15)-C(16)	40.8(8)
C(6)-C(5)-C(15)-C(16)	-88.7(7)

C(20)-C(15)-C(16)-C(17)	3.5(10)
C(5)-C(15)-C(16)-C(17)	-177.9(6)
C(15)-C(16)-C(17)-C(18)	-4.1(11)
C(16)-C(17)-C(18)-C(19)	4.1(12)
C(17)-C(18)-C(19)-C(20)	-3.8(11)
C(18)-C(19)-C(20)-C(15)	3.6(11)
C(16)-C(15)-C(20)-C(19)	-3.3(10)
C(5)-C(15)-C(20)-C(19)	178.1(6)
C(7)-C(6)-C(21)-O(1)	-104.4(8)
C(1)-C(6)-C(21)-O(1)	135.5(7)
C(5)-C(6)-C(21)-O(1)	18.9(10)
C(7)-C(6)-C(21)-O(2)	72.9(7)
C(1)-C(6)-C(21)-O(2)	-47.3(7)
C(5)-C(6)-C(21)-O(2)	-163.8(6)
C(4)-C(3)-C(23)-O(3)	-165.8(7)
C(2)-C(3)-C(23)-O(3)	13.3(9)
C(4)-C(3)-C(23)-O(4)	15.8(8)
C(2)-C(3)-C(23)-O(4)	-165.1(5)
O(1)-C(21)-O(2)-C(22)	1.8(10)
C(6)-C(21)-O(2)-C(22)	-175.6(6)
O(3)-C(23)-O(4)-C(24)	3.0(10)
C(3)-C(23)-O(4)-C(24)	-178.6(6)

Symmetry transformations used to generate equivalent atoms:

3: X-ray crystallographic structure of 4.17h



4.17h

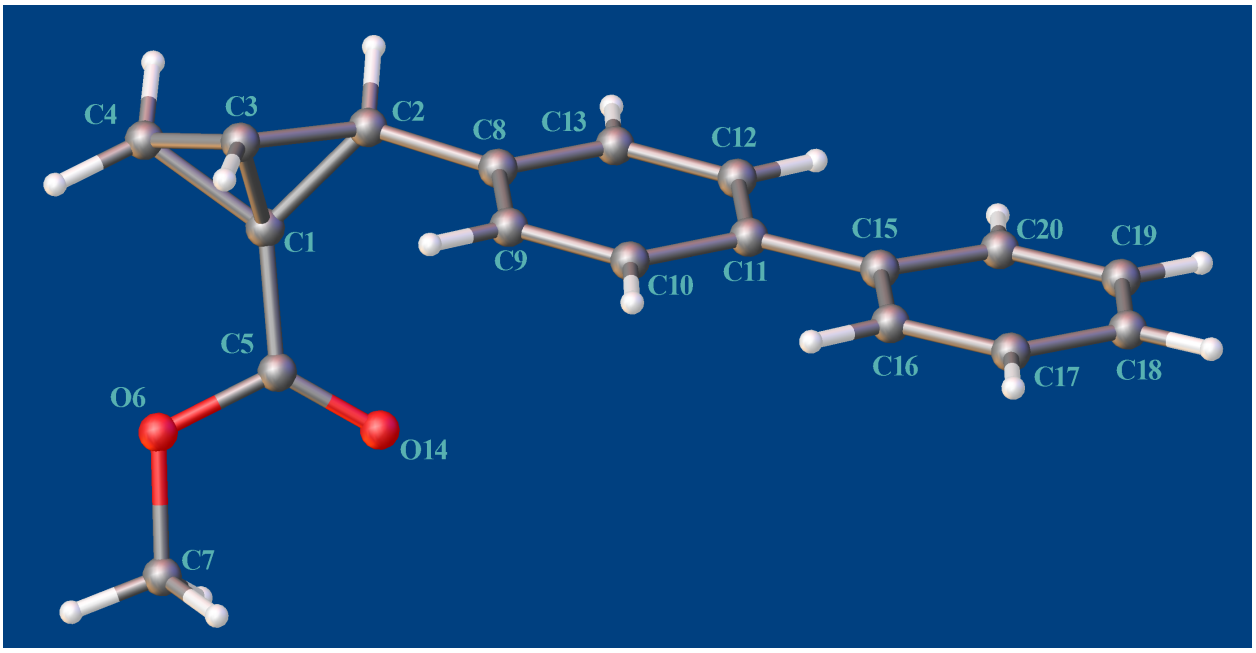


Table 1. Crystal data and structure refinement for **4.17h**_fin.

Identification code	28shells	
Empirical formula	C18 H16 O2	
Formula weight	264.31	
Temperature	173 K	
Wavelength	1.54184 Å	
Crystal system	Monoclinic	
Space group	P 21	
Unit cell dimensions	a = 10.1737(19) Å	a= 90°.
	b = 5.6370(11) Å	b= 110.394(14)°.
	c = 12.798(3) Å	g = 90°.
Volume	687.9(2) $Å^3$	
Z	2	
Density (calculated)	1.276 Mg/m^3	
Absorption coefficient	0.650 mm^{-1}	

F(000)	280
Crystal size	0.46 x 0.13 x 0.05 mm^3
Theta range for data collection	3.68 to 60.00°.
Index ranges	-10<=h<=8, -6<=k<=6, -14<=l<=13
Reflections collected	8441
Independent reflections	1751 [R(int) = 0.0679]
Completeness to theta = 60.00°	95 %
Absorption correction	Semi-empirical from equivalents
Max. and min. transmission	0.8643 and 0.7638
Refinement method	Full-matrix least-squares on F^2
Data / restraints / parameters	1751 / 7 / 198
Goodness-of-fit on F^2	1.061
Final R indices [I>2sigma(I)]	R1 = 0.0478, wR2 = 0.1096
R indices (all data)	R1 = 0.0852, wR2 = 0.1355
Absolute structure parameter	0.1(6)
Largest diff. peak and hole	0.165 and -0.201 e.$Å^{-3}$

Table 2. Atomic coordinates (x 10^4) and equivalent isotropic displacement parameters ($Å^2$x 10^3) for **4.17h**_fin. U(eq) is defined as one third of the trace of the orthogonalized U^{ij} tensor.

	x	y	z	U(eq)
O(6)	7910(3)	8485(6)	5536(3)	56(1)
O(14)	6572(3)	6628(7)	6352(3)	59(1)
C(1)	8777(4)	5037(9)	6520(3)	45(2)
C(2)	9194(4)	3435(9)	7530(4)	45(2)
C(3)	10213(4)	5255(10)	7420(4)	48(2)
C(4)	10088(5)	4814(10)	6248(4)	54(2)
C(5)	7631(4)	6751(9)	6149(4)	46(2)
C(7)	6787(5)	10205(11)	5097(4)	65(2)
C(8)	8555(4)	3648(9)	8411(3)	41(2)
C(9)	8806(4)	5551(8)	9138(4)	51(2)
C(10)	8231(4)	5668(8)	9958(4)	48(2)
C(11)	7389(4)	3905(8)	10128(3)	38(2)
C(12)	7132(4)	1986(8)	9386(4)	50(2)
C(13)	7699(4)	1879(9)	8553(4)	52(2)
C(15)	6811(4)	3994(8)	11039(3)	39(2)
C(16)	7108(5)	5863(9)	11789(4)	59(2)
C(17)	6603(5)	5970(10)	12654(4)	64(2)
C(18)	5748(4)	4213(9)	12797(4)	50(2)
C(19)	5410(4)	2359(9)	12056(4)	51(2)
C(20)	5923(4)	2255(9)	11190(4)	52(2)

Table 3. Bond lengths [Å] and angles [°] for **4.17h**_fin.

O(6)-C(5)	1.344(6)
O(6)-C(7)	1.454(7)
O(14)-C(5)	1.195(6)
C(1)-C(2)	1.511(6)
C(1)-C(3)	1.518(6)
C(1)-C(4)	1.497(7)
C(1)-C(5)	1.460(7)
C(2)-C(3)	1.500(7)
C(2)-C(8)	1.490(6)
C(3)-C(4)	1.482(7)
C(8)-C(9)	1.384(6)
C(8)-C(13)	1.377(7)
C(9)-C(10)	1.370(7)
C(10)-C(11)	1.378(6)
C(11)-C(12)	1.403(6)
C(11)-C(15)	1.478(6)
C(12)-C(13)	1.379(7)
C(15)-C(16)	1.386(6)
C(15)-C(20)	1.392(6)
C(16)-C(17)	1.375(7)
C(17)-C(18)	1.372(7)
C(18)-C(19)	1.372(7)
C(19)-C(20)	1.381(7)
C(2)-H(2)	1.03(3)
C(3)-H(3)	1.03(4)
C(4)-H(4A)	1.03(3)
C(4)-H(4B)	1.03(5)
C(7)-H(7A)	0.9800
C(7)-H(7B)	0.9800
C(7)-H(7C)	0.9800
C(9)-H(9)	0.9500
C(10)-H(10)	0.9500
C(12)-H(12)	0.9500
C(13)-H(13)	0.9500

C(16)-H(16)	0.9500
C(17)-H(17)	0.9500
C(18)-H(18)	0.9500
C(19)-H(19)	0.9500
C(20)-H(20)	0.9500
C(5)-O(6)-C(7)	114.4(4)
C(2)-C(1)-C(3)	59.4(3)
C(2)-C(1)-C(4)	98.1(4)
C(2)-C(1)-C(5)	128.9(4)
C(3)-C(1)-C(4)	58.9(3)
C(3)-C(1)-C(5)	129.9(4)
C(4)-C(1)-C(5)	130.9(4)
C(1)-C(2)-C(3)	60.5(3)
C(1)-C(2)-C(8)	122.2(4)
C(3)-C(2)-C(8)	120.9(4)
C(1)-C(3)-C(2)	60.1(3)
C(1)-C(3)-C(4)	59.9(3)
C(2)-C(3)-C(4)	99.3(4)
C(1)-C(4)-C(3)	61.3(3)
O(6)-C(5)-O(14)	124.0(5)
O(6)-C(5)-C(1)	111.3(4)
O(14)-C(5)-C(1)	124.7(5)
C(2)-C(8)-C(9)	123.0(4)
C(2)-C(8)-C(13)	120.3(4)
C(9)-C(8)-C(13)	116.7(4)
C(8)-C(9)-C(10)	121.6(4)
C(9)-C(10)-C(11)	122.8(4)
C(10)-C(11)-C(12)	115.4(4)
C(10)-C(11)-C(15)	122.7(4)
C(12)-C(11)-C(15)	121.9(4)
C(11)-C(12)-C(13)	121.9(4)
C(8)-C(13)-C(12)	121.6(4)
C(11)-C(15)-C(16)	121.4(4)
C(11)-C(15)-C(20)	122.8(4)
C(16)-C(15)-C(20)	115.8(4)
C(15)-C(16)-C(17)	122.6(5)

C(16)-C(17)-C(18)	120.5(5)
C(17)-C(18)-C(19)	118.4(4)
C(18)-C(19)-C(20)	120.9(4)
C(15)-C(20)-C(19)	121.8(4)
C(1)-C(2)-H(2)	113(3)
C(3)-C(2)-H(2)	117(2)
C(8)-C(2)-H(2)	114(3)
C(1)-C(3)-H(3)	124(3)
C(2)-C(3)-H(3)	130(3)
C(4)-C(3)-H(3)	127(3)
C(1)-C(4)-H(4A)	110(2)
C(1)-C(4)-H(4B)	118(3)
C(3)-C(4)-H(4A)	116(3)
C(3)-C(4)-H(4B)	113(3)
H(4A)-C(4)-H(4B)	123(4)
O(6)-C(7)-H(7A)	109.00
O(6)-C(7)-H(7B)	110.00
O(6)-C(7)-H(7C)	110.00
H(7A)-C(7)-H(7B)	109.00
H(7A)-C(7)-H(7C)	109.00
H(7B)-C(7)-H(7C)	109.00
C(8)-C(9)-H(9)	119.00
C(10)-C(9)-H(9)	119.00
C(9)-C(10)-H(10)	119.00
C(11)-C(10)-H(10)	119.00
C(11)-C(12)-H(12)	119.00
C(13)-C(12)-H(12)	119.00
C(8)-C(13)-H(13)	119.00
C(12)-C(13)-H(13)	119.00
C(15)-C(16)-H(16)	119.00
C(17)-C(16)-H(16)	119.00
C(16)-C(17)-H(17)	120.00
C(18)-C(17)-H(17)	120.00
C(17)-C(18)-H(18)	121.00
C(19)-C(18)-H(18)	121.00
C(18)-C(19)-H(19)	120.00

C(20)-C(19)-H(19)	120.00
C(15)-C(20)-H(20)	119.00
C(19)-C(20)-H(20)	119.00

Table 4. Anisotropic displacement parameters ($Å^2 x\ 10^3$)for **4.17h**_fin. The anisotropic displacement factor exponent takes the form: $-2p^2[\ h^2a^{*2}U^{11} + ... + 2\ h\ k\ a^*\ b^*\ U^{12}\ ]$

	U^{11}	U^{22}	U^{33}	U^{23}	U^{13}	U^{12}
O(6)	45(2)	62(2)	64(2)	12(2)	21(1)	8(1)
O(14)	43(2)	68(2)	71(2)	17(2)	25(2)	10(1)
C(1)	30(2)	54(3)	51(3)	6(3)	14(2)	8(2)
C(2)	39(2)	45(3)	50(3)	3(3)	13(2)	6(2)
C(3)	39(2)	57(4)	49(3)	1(3)	17(2)	7(2)
C(4)	50(3)	62(4)	56(3)	-1(3)	27(2)	10(3)
C(5)	41(3)	56(3)	41(3)	-7(3)	15(2)	-9(2)
C(7)	59(3)	64(4)	66(3)	16(3)	14(2)	16(3)
C(8)	33(2)	39(3)	46(3)	1(3)	7(2)	5(2)
C(9)	47(3)	44(3)	65(3)	-1(3)	25(2)	-10(2)
C(10)	46(3)	40(3)	63(3)	-10(3)	26(2)	-10(2)
C(11)	30(2)	31(3)	46(3)	-1(2)	5(2)	2(2)
C(12)	48(3)	39(3)	67(3)	-3(3)	25(2)	-13(2)
C(13)	48(3)	41(3)	65(3)	-16(3)	19(2)	-6(2)
C(15)	30(2)	37(3)	46(3)	1(2)	8(2)	3(2)
C(16)	60(3)	52(4)	79(4)	-25(3)	41(3)	-25(2)
C(17)	66(3)	63(4)	78(4)	-22(3)	43(3)	-20(2)
C(18)	40(3)	58(4)	51(3)	7(3)	14(2)	3(2)
C(19)	47(3)	52(4)	57(3)	8(3)	21(2)	-8(2)
C(20)	48(3)	43(3)	66(4)	-9(3)	20(2)	-12(2)

Table 5. Hydrogen coordinates ($x\ 10^4$) and isotropic displacement parameters ($Å^2 x\ 10^3$) for **4.17h**_fin.

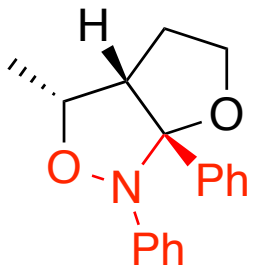
	x	y	z	U(eq)
H(2)	9370(40)	1710(50)	7350(40)	58(13)
H(3)	10580(50)	6770(70)	7880(40)	91(18)
H(4A)	10210(40)	3080(50)	6040(40)	46(12)
H(4B)	10400(50)	6250(70)	5890(40)	84(17)
H(7A)	6626	11028	5716	97
H(7B)	5926	9386	4646	97
H(7C)	7050	11362	4633	97
H(9)	9391	6807	9066	60
H(10)	8421	7022	10430	57
H(12)	6550	725	9458	60
H(13)	7495	551	8066	62
H(16)	7683	7120	11702	71
H(17)	6848	7271	13157	77
H(18)	5399	4278	13395	60
H(19)	4815	1131	12140	62
H(20)	5662	961	10683	63

Table 6. Torsion angles [°] for **4.17h**_fin.

C(7)-O(6)-C(5)-O(14)	-1.9(7)
C(7)-O(6)-C(5)-C(1)	177.5(4)
C(4)-C(1)-C(2)-C(8)	156.3(4)
C(3)-C(1)-C(2)-C(8)	110.0(5)
C(4)-C(1)-C(2)-C(3)	46.2(4)
C(2)-C(1)-C(3)-C(4)	123.4(4)
C(4)-C(1)-C(3)-C(2)	-123.4(4)
C(5)-C(1)-C(3)-C(2)	117.1(5)
C(5)-C(1)-C(3)-C(4)	-119.5(6)
C(2)-C(1)-C(4)-C(3)	-46.5(4)
C(5)-C(1)-C(2)-C(3)	-118.7(6)
C(5)-C(1)-C(2)-C(8)	-8.7(7)
C(2)-C(1)-C(5)-O(14)	-26.6(8)
C(3)-C(1)-C(5)-O(6)	74.4(6)
C(3)-C(1)-C(5)-O(14)	-106.3(6)
C(4)-C(1)-C(5)-O(6)	-6.0(7)
C(4)-C(1)-C(5)-O(14)	173.3(5)
C(5)-C(1)-C(4)-C(3)	117.9(6)
C(2)-C(1)-C(5)-O(6)	154.0(5)
C(1)-C(2)-C(3)-C(4)	-47.1(4)
C(1)-C(2)-C(8)-C(9)	-69.6(6)
C(1)-C(2)-C(8)-C(13)	112.1(5)
C(3)-C(2)-C(8)-C(9)	2.9(7)
C(3)-C(2)-C(8)-C(13)	-175.4(4)
C(8)-C(2)-C(3)-C(1)	-112.0(5)
C(8)-C(2)-C(3)-C(4)	-159.1(4)
C(2)-C(3)-C(4)-C(1)	47.2(4)
C(2)-C(8)-C(9)-C(10)	-178.3(4)
C(13)-C(8)-C(9)-C(10)	0.0(7)
C(2)-C(8)-C(13)-C(12)	177.7(4)
C(9)-C(8)-C(13)-C(12)	-0.7(7)
C(8)-C(9)-C(10)-C(11)	1.0(7)
C(9)-C(10)-C(11)-C(12)	-1.3(7)
C(9)-C(10)-C(11)-C(15)	177.7(4)

C(10)-C(11)-C(12)-C(13)	0.6(6)
C(15)-C(11)-C(12)-C(13)	-178.4(4)
C(10)-C(11)-C(15)-C(16)	-1.0(7)
C(10)-C(11)-C(15)-C(20)	177.8(4)
C(12)-C(11)-C(15)-C(16)	177.9(4)
C(12)-C(11)-C(15)-C(20)	-3.3(7)
C(11)-C(12)-C(13)-C(8)	0.4(7)
C(11)-C(15)-C(16)-C(17)	-178.9(5)
C(20)-C(15)-C(16)-C(17)	2.2(7)
C(11)-C(15)-C(20)-C(19)	179.1(4)
C(16)-C(15)-C(20)-C(19)	-2.0(7)
C(15)-C(16)-C(17)-C(18)	-1.2(8)
C(16)-C(17)-C(18)-C(19)	-0.1(8)
C(17)-C(18)-C(19)-C(20)	0.3(7)
C(18)-C(19)-C(20)-C(15)	0.8(7)

4: X-ray crystallographic structure of 5.39



5.39

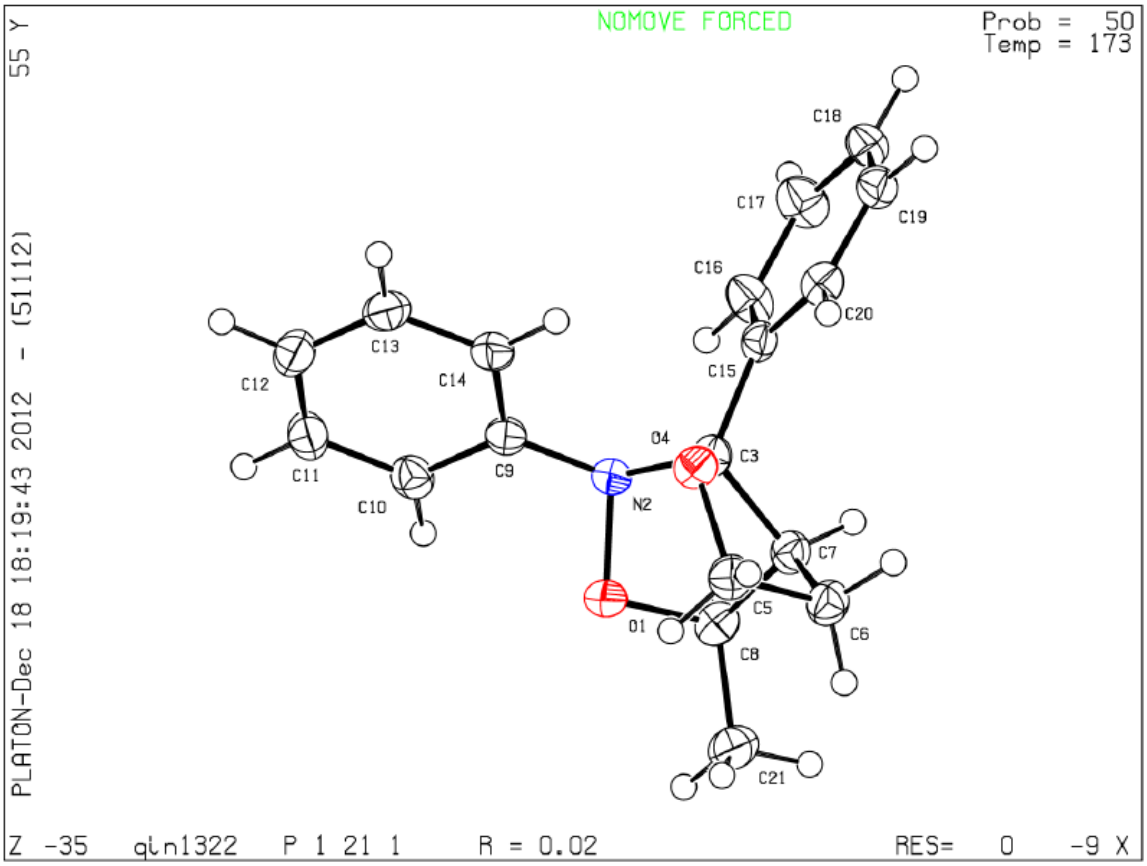


Table 1. Crystal data and structure refinement for **5.39**_fin.

Identification code	qin1322	
Empirical formula	C36 H38 N2 O4	
Formula weight	562.68	
Temperature	173(2) K	
Wavelength	1.54178 ≈	
Crystal system	Monoclinic	
Space group	P 1 21 1	
Unit cell dimensions	a = 6.5770(2) ≈	a= 90∞.
	b = 13.6444(5) ≈	b= 91.519(3)∞.
	c = 8.0893(3) ≈	g = 90∞.
Volume	725.67(4) $\approx^3$	
Z	1	
Density (calculated)	1.288 Mg/m^3	
Absorption coefficient	0.665 mm^{-1}	

F(000)	300
Crystal size	0.652 x 0.563 x 0.146 mm^3
Theta range for data collection	5.470 to 68.095∞.
Index ranges	-7<=h<=6, -16<=k<=14, -9<=l<=9
Reflections collected	4212
Independent reflections	2136 [R(int) = 0.0126]
Completeness to theta = 67.500∞	96.2 %
Absorption correction	Semi-empirical from equivalents
Max. and min. transmission	0.7530 and 0.6729
Refinement method	Full-matrix least-squares on F^2
Data / restraints / parameters	2136 / 30 / 253
Goodness-of-fit on F^2	1.078
Final R indices [I>2sigma(I)]	R1 = 0.0234, wR2 = 0.0596
R indices (all data)	R1 = 0.0237, wR2 = 0.0599
Absolute structure parameter	0.06(6)
Extinction coefficient	n/a
Largest diff. peak and hole	0.135 and -0.153 $e.\approx^{-3}$

Table 2. Atomic coordinates (x 10^4) and equivalent isotropic displacement parameters ($\approx^2$x 10^3) for **5.39**_fin. U(eq) is defined as one third of the trace of the orthogonalized U^{ij} tensor.

	x	y	z	U(eq)
O(4)	5060(2)	4783(1)	6822(2)	26(1)
C(9)	1347(3)	5989(1)	6864(2)	24(1)
C(3)	3489(3)	4665(1)	5594(2)	24(1)
C(15)	4144(3)	5102(1)	3963(2)	23(1)
C(14)	2914(3)	6679(2)	6896(2)	28(1)
C(20)	6178(3)	5162(1)	3570(2)	27(1)
C(5)	5224(3)	3896(2)	7780(2)	29(1)
C(19)	6715(3)	5438(1)	1990(2)	29(1)
C(10)	-519(3)	6234(2)	7551(2)	28(1)
C(13)	2619(3)	7589(2)	7627(2)	33(1)
C(7)	3035(3)	3546(1)	5477(2)	26(1)
C(8)	857(3)	3460(1)	6083(2)	28(1)
C(18)	5247(3)	5675(2)	804(2)	31(1)
C(11)	-779(3)	7142(2)	8274(2)	33(1)
C(12)	785(3)	7822(2)	8324(2)	34(1)
C(16)	2673(3)	5342(2)	2759(2)	33(1)
C(6)	4746(3)	3092(2)	6546(3)	30(1)
C(17)	3223(3)	5632(2)	1199(2)	38(1)
O(1)	598(2)	4316(1)	7090(2)	28(1)
N(2)	1519(2)	5072(1)	6070(2)	24(1)
C(21)	360(3)	2569(2)	7088(3)	37(1)

Table 3. Bond lengths [≈] and angles [∞] for **5.39**_fin.

O(4)-C(3)	1.424(2)
O(4)-C(5)	1.438(2)
C(9)-C(14)	1.395(3)
C(9)-C(10)	1.401(3)
C(9)-N(2)	1.412(2)
C(3)-C(15)	1.521(2)
C(3)-C(7)	1.557(3)
C(3)-N(2)	1.470(2)
C(15)-C(20)	1.386(3)
C(15)-C(16)	1.394(2)
C(14)-C(13)	1.392(3)
C(20)-C(19)	1.387(3)
C(5)-C(6)	1.511(3)
C(19)-C(18)	1.381(3)
C(10)-C(11)	1.383(3)
C(13)-C(12)	1.382(3)
C(7)-C(8)	1.531(3)
C(7)-C(6)	1.532(3)
C(8)-O(1)	1.437(2)
C(8)-C(21)	1.503(3)
C(18)-C(17)	1.378(3)
C(11)-C(12)	1.385(3)
C(16)-C(17)	1.379(3)
O(1)-N(2)	1.4623(19)
C(3)-O(4)-C(5)	108.85(14)
C(14)-C(9)-C(10)	119.12(17)
C(14)-C(9)-N(2)	122.52(16)
C(10)-C(9)-N(2)	118.23(16)
O(4)-C(3)-C(15)	110.10(14)
O(4)-C(3)-C(7)	106.74(14)
O(4)-C(3)-N(2)	113.77(14)
C(15)-C(3)-C(7)	112.95(15)
N(2)-C(3)-C(15)	110.51(14)

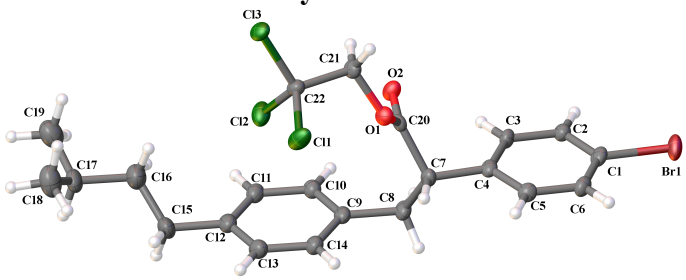
N(2)-C(3)-C(7)	102.58(14)
C(20)-C(15)-C(3)	121.30(15)
C(20)-C(15)-C(16)	118.86(16)
C(16)-C(15)-C(3)	119.41(16)
C(13)-C(14)-C(9)	119.91(18)
C(15)-C(20)-C(19)	119.86(16)
O(4)-C(5)-C(6)	104.11(15)
C(18)-C(19)-C(20)	120.89(18)
C(11)-C(10)-C(9)	120.03(19)
C(12)-C(13)-C(14)	120.77(19)
C(8)-C(7)-C(3)	103.61(15)
C(8)-C(7)-C(6)	117.89(16)
C(6)-C(7)-C(3)	103.01(15)
O(1)-C(8)-C(7)	104.18(14)
O(1)-C(8)-C(21)	108.67(15)
C(21)-C(8)-C(7)	117.03(16)
C(17)-C(18)-C(19)	119.38(18)
C(10)-C(11)-C(12)	120.9(2)
C(13)-C(12)-C(11)	119.32(19)
C(17)-C(16)-C(15)	120.83(18)
C(5)-C(6)-C(7)	102.45(16)
C(18)-C(17)-C(16)	120.16(18)
C(8)-O(1)-N(2)	101.35(12)
C(9)-N(2)-C(3)	122.40(14)
C(9)-N(2)-O(1)	109.21(13)
O(1)-N(2)-C(3)	105.17(13)

Symmetry transformations used to generate equivalent atoms:

5: X-ray crystallographic structure of 7.30

Crystal data and experimental

Crystal submitted by: **Changming Qin, ID-QIN-15-59**
13l Structure solved by John Bacsa



Experimental. Single crystals of $C_{22}H_{24}BrCl_3O_2$ (**435**) were recrystallised from hexane by slow evaporation. A suitable crystal (0.557×0.250×0.136 mm^3) was selected and mounted on a loop in perflourotether oil on a ApexII Mo diffractometer. The crystal was kept at 110(2) K during data collection. Using Olex2 [1], the structure was solved with the XT [2] structure solution program, using the Direct Methods solution method. The model was refined with the ShelXL [3] refinement package using Least Squares minimisation.

Crystal Data. $C_{22}H_{24}BrCl_3O_2$, M = 506.67, monoclinic, $P2_1$ (No. 4, a = 11.0837 Å, b = 5.761 Å, c = 18.212 Å, b = 105.1848°, a = g = 90°,V = 1122.3(2) $Å^3$, T = 110(2) K, Z = 2, m (Mo K_a) = 2.204, 19633 reflections measured, 4787 unique (R_{int} = 0.0490) which were used in all calculations. The final wR_2 was 0.1049 (all data) and R_1 was 0.0425 (I > 2(I)).

[1] Olex2 (Dolomanov et al., 2009)
[2] XT (Sheldrick, 2008)
[3] ShelXL (Sheldrick, 2008)

[3] ShelXL (Sheldrick, 2008)

Compound	QIN-15-59
CCDC	
Formula	$C_{22}H_{24}BrCl_3O_2$
D calc./g cm^{-3}	1.499
m/mm^{-1}	2.204
Formula Weight	506.67
Colour	colourless
Shape	needle
Size/mm^3	0.557×0.250×0.136
T/K	110(2)
Crystal System	monoclinic
Space Group	$P2_1$
a/Å	11.0837(14)
b/Å	5.7610(7)
c/Å	18.212(2)
a/°	90
b/°	105.1848(16)
g/°	90
V/$Å^3$	1122.3(2)
Z	2
Theta min/°	1.904
Theta max/°	26.372
Measured Refl.	19633
Independent Refl.	4787
Reflections Used	4370
R(int)	0.0490
Parameters	256
Restraints	202
Largest Peak	1.136
Deepest Hole	-0.352
GooF	1.080
wR_2(all data)	0.1049
wR_2	0.0982
R_1(all data)	0.0482
R_1	0.0425

Table 1. Crystal data and structure refinement for **7.30**.

Identification code	QIN-15-59	
Empirical formula	C22 H24 Br Cl3 O2	
Formula weight	506.67	
Temperature	110(2) K	
Wavelength	0.71073 Å	
Crystal system	Monoclinic	
Space group	P 1 21 1	
Unit cell dimensions	a = 11.0837(14) Å	a= 90°.
	b = 5.7610(7) Å	b= 105.1848(16)°.
	c = 18.212(2) Å	g = 90°.
Volume	1122.3(2) $Å^3$	
Z	2	
Density (calculated)	1.499 Mg/m^3	
Absorption coefficient	2.204 mm^{-1}	
F(000)	516	
Crystal size	0.557 x 0.25 x 0.136 mm^3	
Theta range for data collection	1.904 to 26.372°.	
Index ranges	-13<=h<=13, -7<=k<=7, -22<=l<=22	
Reflections collected	19633	
Independent reflections	4787 [R(int) = 0.0490]	
Completeness to theta = 26.000°	99.9 %	
Absorption correction	Semi-empirical from equivalents	
Max. and min. transmission	0.745553 and 0.447631	
Refinement method	Full-matrix least-squares on F^2	
Data / restraints / parameters	4787 / 202 / 256	
Goodness-of-fit on F^2	1.080	
Final R indices [I>2sigma(I)]	R1 = 0.0425, wR2 = 0.0982	
R indices (all data)	R1 = 0.0482, wR2 = 0.1049	
Absolute structure parameter	0.028(6)	
Extinction coefficient	n/a	
Largest diff. peak and hole	1.136 and -0.352 e.$Å^{-3}$	

Table 2. Atomic coordinates (x 10^4) and equivalent isotropic displacement parameters ($Å^2$x 10^3)
for **7.30**. U(eq) is defined as one third of the trace of the orthogonalized U^{ij} tensor.

	x	y	z	U(eq)
Br(1)	5806(1)	5071(1)	6849(1)	32(1)
Cl(3)	5696(1)	7797(2)	678(1)	26(1)
Cl(1)	6075(2)	3156(2)	1275(1)	35(1)
Cl(2)	8088(1)	6490(3)	1683(1)	34(1)
O(2)	7646(3)	8064(7)	3505(2)	24(1)
O(1)	6434(3)	5325(7)	2775(2)	22(1)
C(6)	6075(5)	2788(11)	5507(3)	24(1)
C(1)	6380(5)	4748(11)	5949(3)	24(1)
C(14)	9703(5)	2199(10)	3033(3)	24(1)
C(3)	7499(5)	6308(10)	5109(3)	21(1)
C(21)	5985(5)	6909(10)	2160(3)	23(1)
C(5)	6505(5)	2601(10)	4856(3)	22(1)
C(9)	9796(5)	4015(10)	3553(3)	22(1)
C(20)	7298(5)	6093(9)	3404(3)	18(1)
C(4)	7213(5)	4359(9)	4650(3)	20(1)
C(8)	9167(5)	3935(11)	4190(3)	25(1)
C(13)	10307(5)	2319(11)	2457(3)	28(1)
C(12)	11032(5)	4242(10)	2378(3)	28(1)
C(2)	7097(5)	6533(10)	5771(3)	22(1)
C(11)	11128(5)	6049(11)	2895(3)	25(1)
C(7)	7717(5)	4067(10)	3949(3)	20(1)
C(10)	10514(5)	5937(10)	3478(3)	24(1)
C(17)	12200(6)	6650(13)	666(4)	38(1)
C(19)	12482(7)	9153(14)	531(5)	48(2)
C(15)	11684(7)	4344(12)	1745(4)	40(2)
C(22)	6449(5)	6127(9)	1485(3)	21(1)
C(18)	11442(7)	5563(16)	-56(4)	51(2)
C(16)	11617(7)	6598(15)	1339(4)	47(2)

Table 3. Bond lengths [Å] and angles [°] for **7.30**.

Br(1)-C(1)	1.916(5)
Cl(3)-C(22)	1.772(5)
Cl(1)-C(22)	1.779(6)
Cl(2)-C(22)	1.769(6)
O(2)-C(20)	1.198(7)
O(1)-C(21)	1.428(6)
O(1)-C(20)	1.361(6)
C(6)-C(1)	1.376(8)
C(6)-C(5)	1.393(8)
C(1)-C(2)	1.389(8)
C(14)-C(9)	1.397(8)
C(14)-C(13)	1.385(8)
C(3)-C(4)	1.386(8)
C(3)-C(2)	1.396(7)
C(21)-C(22)	1.520(7)
C(5)-C(4)	1.391(8)
C(9)-C(8)	1.503(8)
C(9)-C(10)	1.391(8)
C(20)-C(7)	1.523(8)
C(4)-C(7)	1.531(7)
C(8)-C(7)	1.553(7)
C(13)-C(12)	1.398(9)
C(12)-C(11)	1.389(8)
C(12)-C(15)	1.513(8)
C(11)-C(10)	1.403(8)
C(17)-C(19)	1.509(11)
C(17)-C(18)	1.500(10)
C(17)-C(16)	1.527(9)
C(15)-C(16)	1.487(10)
C(20)-O(1)-C(21)	118.5(4)
C(1)-C(6)-C(5)	118.3(5)
C(6)-C(1)-Br(1)	119.6(4)
C(6)-C(1)-C(2)	122.6(5)

C(2)-C(1)-Br(1)	117.8(4)
C(13)-C(14)-C(9)	120.8(6)
C(4)-C(3)-C(2)	121.4(5)
O(1)-C(21)-C(22)	108.8(4)
C(4)-C(5)-C(6)	121.0(5)
C(14)-C(9)-C(8)	122.3(5)
C(10)-C(9)-C(14)	118.1(5)
C(10)-C(9)-C(8)	119.6(5)
O(2)-C(20)-O(1)	124.4(5)
O(2)-C(20)-C(7)	126.5(5)
O(1)-C(20)-C(7)	109.1(4)
C(3)-C(4)-C(5)	118.9(5)
C(3)-C(4)-C(7)	121.1(5)
C(5)-C(4)-C(7)	119.9(5)
C(9)-C(8)-C(7)	115.8(4)
C(14)-C(13)-C(12)	121.5(6)
C(13)-C(12)-C(15)	120.8(6)
C(11)-C(12)-C(13)	117.9(5)
C(11)-C(12)-C(15)	121.3(6)
C(1)-C(2)-C(3)	117.6(5)
C(12)-C(11)-C(10)	120.8(5)
C(20)-C(7)-C(4)	110.1(4)
C(20)-C(7)-C(8)	109.7(5)
C(4)-C(7)-C(8)	110.2(4)
C(9)-C(10)-C(11)	120.9(5)
C(19)-C(17)-C(16)	107.4(6)
C(18)-C(17)-C(19)	110.4(6)
C(18)-C(17)-C(16)	116.0(6)
C(16)-C(15)-C(12)	116.2(5)
Cl(3)-C(22)-Cl(1)	108.2(3)
Cl(2)-C(22)-Cl(3)	109.9(3)
Cl(2)-C(22)-Cl(1)	109.1(3)
C(21)-C(22)-Cl(3)	108.9(4)
C(21)-C(22)-Cl(1)	110.4(4)
C(21)-C(22)-Cl(2)	110.3(4)
C(15)-C(16)-C(17)	116.1(6)

Table 4. Anisotropic displacement parameters ($Å^2 x\ 10^3$) for **7.30**. The anisotropic displacement factor exponent takes the form: $-2p^2[\ h^2\ a^{*2}U^{11} + ...\ + 2\ h\ k\ a^*\ b^*\ U^{12}\ ]$

	U^{11}	U^{22}	U^{33}	U^{23}	U^{13}	U^{12}
Br(1)	30(1)	51(1)	18(1)	4(1)	12(1)	0(1)
Cl(3)	34(1)	27(1)	14(1)	2(1)	2(1)	5(1)
Cl(1)	61(1)	21(1)	21(1)	-4(1)	8(1)	-3(1)
Cl(2)	25(1)	54(1)	25(1)	9(1)	7(1)	4(1)
O(2)	32(2)	21(2)	18(2)	-1(2)	6(2)	-4(2)
O(1)	26(2)	24(2)	16(2)	-3(2)	3(1)	0(2)
C(6)	22(2)	29(3)	22(3)	6(2)	7(2)	-3(2)
C(1)	23(2)	32(3)	15(2)	6(2)	3(2)	1(2)
C(14)	28(3)	27(3)	20(2)	4(2)	7(2)	3(2)
C(3)	22(2)	24(3)	18(2)	3(2)	8(2)	-3(2)
C(21)	29(3)	26(3)	14(2)	-2(2)	5(2)	4(2)
C(5)	22(2)	24(3)	19(2)	-1(2)	2(2)	-2(2)
C(9)	22(2)	27(2)	16(2)	4(2)	4(2)	5(2)
C(20)	21(2)	22(3)	15(2)	-4(2)	8(2)	2(2)
C(4)	18(2)	27(3)	14(2)	4(2)	2(2)	3(2)
C(8)	26(2)	32(3)	16(2)	4(2)	6(2)	4(2)
C(13)	37(3)	26(3)	22(2)	0(2)	10(2)	5(2)
C(12)	30(3)	32(3)	22(2)	6(2)	9(2)	8(2)
C(2)	24(3)	23(3)	17(2)	2(2)	5(2)	2(2)
C(11)	22(2)	30(3)	23(2)	5(2)	6(2)	2(2)
C(7)	25(2)	20(2)	15(2)	-2(2)	7(2)	0(2)
C(10)	24(2)	27(3)	18(2)	0(2)	5(2)	3(2)
C(17)	36(3)	50(3)	33(3)	7(3)	21(2)	11(3)
C(19)	46(4)	51(3)	54(4)	-5(3)	24(3)	2(3)
C(15)	51(4)	40(3)	40(3)	7(2)	30(3)	16(3)
C(22)	27(2)	19(2)	17(2)	1(2)	4(2)	3(2)
C(18)	51(4)	60(5)	49(3)	-9(3)	27(3)	-9(3)
C(16)	57(4)	50(4)	44(3)	8(3)	30(3)	12(3)

Table 5. Hydrogen coordinates ($x\ 10^4$) and isotropic displacement parameters ($Å^2 x\ 10^3$) for **7.30**.

	x	y	z	U(eq)
H(6)	5583	1593	5642	29
H(14)	9220	867	3074	29
H(3)	7980	7516	4971	25
H(21A)	6293	8493	2316	28
H(21B)	5060	6940	2018	28
H(5)	6312	1251	4547	27
H(8A)	9487	5240	4541	30
H(8B)	9415	2478	4478	30
H(13)	10227	1066	2109	33
H(2)	7306	7861	6088	26
H(11)	11615	7376	2854	30
H(7)	7379	2593	3683	23
H(10)	10590	7192	3825	28
H(17)	13014	5803	822	45
H(19A)	12910	9238	124	72
H(19B)	13020	9811	999	72
H(19C)	11699	10033	382	72
H(15A)	12576	3952	1963	48
H(15B)	11321	3129	1367	48
H(18A)	10675	6461	-253	76
H(18B)	11227	3967	46	76
H(18C)	11931	5551	-434	76
H(16A)	12034	7792	1710	57
H(16B)	10726	7045	1153	57

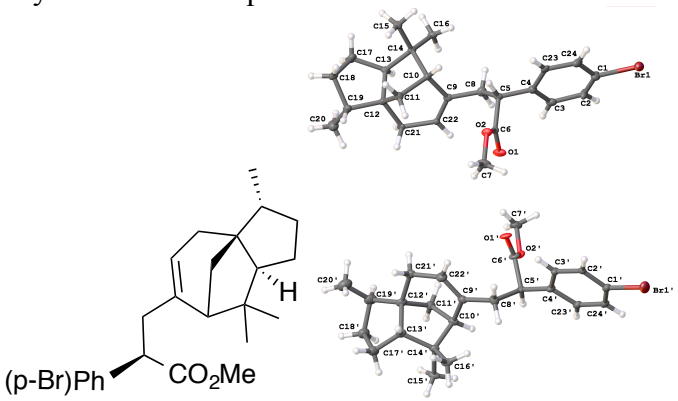
Table 6. Torsion angles [°] for **7.30**.

Br(1)-C(1)-C(2)-C(3)	-179.1(4)
O(2)-C(20)-C(7)-C(4)	69.5(7)
O(2)-C(20)-C(7)-C(8)	-52.0(7)
O(1)-C(21)-C(22)-Cl(3)	170.8(4)
O(1)-C(21)-C(22)-Cl(1)	52.1(5)
O(1)-C(21)-C(22)-Cl(2)	-68.6(5)
O(1)-C(20)-C(7)-C(4)	-109.5(5)
O(1)-C(20)-C(7)-C(8)	129.0(4)
C(6)-C(1)-C(2)-C(3)	0.9(7)
C(6)-C(5)-C(4)-C(3)	0.7(7)
C(6)-C(5)-C(4)-C(7)	177.6(5)
C(1)-C(6)-C(5)-C(4)	-0.8(7)
C(14)-C(9)-C(8)-C(7)	-68.8(7)
C(14)-C(9)-C(10)-C(11)	0.0(7)
C(14)-C(13)-C(12)-C(11)	-0.1(8)
C(14)-C(13)-C(12)-C(15)	-180.0(5)
C(3)-C(4)-C(7)-C(20)	-58.3(6)
C(3)-C(4)-C(7)-C(8)	62.9(6)
C(21)-O(1)-C(20)-O(2)	5.8(7)
C(21)-O(1)-C(20)-C(7)	-175.2(4)
C(5)-C(6)-C(1)-Br(1)	180.0(4)
C(5)-C(6)-C(1)-C(2)	0.0(8)
C(5)-C(4)-C(7)-C(20)	124.8(5)
C(5)-C(4)-C(7)-C(8)	-114.0(5)
C(9)-C(14)-C(13)-C(12)	0.3(8)
C(9)-C(8)-C(7)-C(20)	-49.6(7)
C(9)-C(8)-C(7)-C(4)	-171.0(5)
C(20)-O(1)-C(21)-C(22)	112.0(5)
C(4)-C(3)-C(2)-C(1)	-1.0(7)
C(8)-C(9)-C(10)-C(11)	179.1(5)
C(13)-C(14)-C(9)-C(8)	-179.2(5)
C(13)-C(14)-C(9)-C(10)	-0.2(8)
C(13)-C(12)-C(11)-C(10)	-0.1(8)
C(13)-C(12)-C(15)-C(16)	136.9(7)

C(12)-C(11)-C(10)-C(9)	0.1(8)
C(12)-C(15)-C(16)-C(17)	-176.0(6)
C(2)-C(3)-C(4)-C(5)	0.2(7)
C(2)-C(3)-C(4)-C(7)	-176.7(5)
C(11)-C(12)-C(15)-C(16)	-43.0(9)
C(10)-C(9)-C(8)-C(7)	112.1(6)
C(19)-C(17)-C(16)-C(15)	-158.7(7)
C(15)-C(12)-C(11)-C(10)	179.8(5)
C(18)-C(17)-C(16)-C(15)	77.3(9)

6: X-ray crystallographic structure of 7.42

Crystal data and experimental



Experimental. Single crystals of $C_{24}H_{31}BrO_2$ (**7.42**) were were obtained by recrystallization from hexane and ether. A suitable crystal (0.560×0.203×0.102 mm^3) was selected and was selected and mounted on a Bruker APEX-II CCD diractometer. The crystal was kept at 110(2) K during data collection. Using Olex2 [1], the structure was solved with the ShelXD [2] structure solution program, using the Dual Space solution method. The model was refined with the ShelXL [3] refinement package using Least Squares minimisation.

Crystal Data. $C_{24}H_{31}BrO_2$, M = 431.40, orthorhombic, $P2_12_12_1$ (No. 19, a = 5.7478 Å, b = 19.923 Å, c = 37.012 Å, a = b = g = 90°, V = 4238(2) $Å^3$, T = 110(2) K, Z = 8, m (Mo K_a) = 1.956, 27122 reflections measured, 8520 unique (R_{int} = 0.1062) which were used in all calculations. The final wR_2 was 0.3137 (all data) and R_1 was 0.1315 (I > 2(I)).

[1] Olex2 (Dolomanov et al., 2009)

[2] ShelXD (Sheldrick, 2008)

[3] ShelXL (Sheldrick, 2008)

Compound	QIN-15-126
CCDC	
Formula	$C_{24}H_{31}BrO_2$
D calc./g cm^{-3}	1.352
m/mm^{-1}	1.956
Formula Weight	431.40
Colour	colourless
Shape	plate
Size/mm^3	0.560×0.203×0.102
T/K	110(2)
Crystal System	orthorhombic
Space Group	$P2_12_12_1$
a/Å	5.7478(16)
b/Å	19.923(5)
c/Å	37.012(10)
a/°	90
b/°	90
g/°	90
V/$Å^3$	4238(2)
Z	8
Theta min/°	1.100
Theta max/°	26.370
Measured Refl.	27122
Independent Refl.	8520
Reflections Used	6951
R(int)	0.1062
Parameters	496
Restraints	399
Largest Peak	1.026
Deepest Hole	-1.147
GooF	1.095
wR_2(all data)	0.3137
wR_2	0.3067
R_1(all data)	0.1457
R_1	0.1315

Table 1. Crystal data and structure refinement for **7.42**.

Identification code	QIN-15-126	
Empirical formula	C24 H31 Br O2	
Formula weight	431.40	
Temperature	110(2) K	
Wavelength	0.71073 Å	
Crystal system	Orthorhombic	
Space group	P 21 21 21	
Unit cell dimensions	a = 5.7478(16) Å	a= 90°.
	b = 19.923(5) Å	b= 90°.
	c = 37.012(10) Å	g = 90°.
Volume	4238(2) $Å^3$	
Z	8	
Density (calculated)	1.352 Mg/m^3	
Absorption coefficient	1.956 mm^{-1}	
F(000)	1808	
Crystal size	0.56 x 0.203 x 0.102 mm^3	
Theta range for data collection	1.100 to 26.370°.	
Index ranges	-7<=h<=6, -22<=k<=24, -45<=l<=40	
Reflections collected	27122	
Independent reflections	8520 [R(int) = 0.1062]	
Completeness to theta = 25.242°	102.0 %	
Absorption correction	Semi-empirical from equivalents	
Max. and min. transmission	0.7459 and 0.5463	
Refinement method	Full-matrix least-squares on F^2	
Data / restraints / parameters	8520 / 399 / 496	
Goodness-of-fit on F^2	1.095	
Final R indices [I>2sigma(I)]	R1 = 0.1315, wR2 = 0.3067	
R indices (all data)	R1 = 0.1457, wR2 = 0.3137	
Absolute structure parameter	0.182(14)	
Extinction coefficient	n/a	
Largest diff. peak and hole	1.026 and -1.147 $e.Å^{-3}$	

Table 2. Atomic coordinates (x 10^4) and equivalent isotropic displacement parameters ($Å^2$x 10^3)
for **7.42**. U(eq) is defined as one third of the trace of the orthogonalized U^{ij} tensor.

	x	y	z	U(eq)
Br(1)	915(5)	883(1)	276(1)	26(1)
O(1)	1800(30)	3781(8)	1365(4)	20(3)
O(2)	5610(20)	3893(7)	1187(4)	16(3)
C(1)	1480(40)	1793(11)	418(6)	20(4)
C(9)	1010(30)	5020(10)	739(5)	13(3)
C(17)	1100(50)	7172(11)	330(6)	22(4)
C(5)	2710(40)	3830(11)	725(6)	13(3)
C(14)	1660(30)	5838(10)	211(5)	12(3)
C(3)	220(40)	2795(12)	728(6)	20(4)
C(2)	-260(40)	2113(11)	611(6)	20(5)
C(21)	-10(40)	6038(10)	1088(5)	11(3)
C(6)	3250(40)	3835(10)	1126(5)	11(3)
C(19)	2250(40)	7143(11)	938(6)	15(4)
C(8)	680(40)	4307(11)	647(6)	17(4)
C(20)	250(40)	7535(13)	1114(7)	25(5)
C(10)	2780(30)	5406(10)	529(5)	11(3)
C(15)	3670(40)	6079(10)	-47(5)	15(4)
C(11)	3830(40)	5957(10)	787(5)	16(3)
C(23)	3960(40)	2772(10)	396(5)	17(4)
C(13)	600(40)	6445(10)	440(5)	12(3)
C(22)	-200(30)	5301(10)	1006(5)	10(3)
C(4)	2210(40)	3120(11)	616(6)	16(3)
C(18)	2860(40)	7463(11)	570(6)	18(4)
C(16)	-110(40)	5493(11)	-3(6)	15(4)
C(24)	3520(40)	2105(10)	301(6)	19(4)
C(7)	6190(40)	3890(13)	1565(6)	24(5)
C(12)	1670(40)	6403(10)	825(5)	13(3)
Br(1')	8449(5)	98(1)	2955(1)	32(1)

O(1')	5490(20)	3353(8)	2387(4)	16(3)
O(2')	1800(30)	3202(7)	2546(4)	16(3)
C(15')	2830(30)	4877(13)	4013(5)	17(4)
C(23')	4300(40)	1753(11)	3138(6)	16(3)
C(14')	4800(30)	4808(11)	3727(5)	14(3)
C(2')	8530(40)	1481(10)	2796(5)	14(3)
C(13')	5750(40)	5505(11)	3580(6)	17(3)
C(17')	5040(40)	6125(12)	3790(6)	23(4)
C(7')	1060(40)	3359(12)	2191(6)	20(4)
C(10')	3880(40)	4470(11)	3388(5)	16(3)
C(1')	7230(40)	988(10)	2964(6)	17(3)
C(8')	6510(40)	3472(11)	3158(6)	20(4)
C(4')	5560(40)	2297(10)	2978(6)	16(3)
C(20')	5520(50)	6810(15)	3042(7)	35(6)
C(9')	5810(40)	4201(11)	3154(5)	16(3)
C(22')	6870(40)	4635(11)	2919(6)	21(4)
C(12')	4600(40)	5592(12)	3205(6)	17(3)
C(3')	7660(40)	2120(11)	2804(6)	15(4)
C(6')	4070(40)	3209(11)	2598(6)	16(4)
C(19')	3700(50)	6320(12)	3173(6)	26(4)
C(18')	3040(40)	6460(12)	3561(6)	24(4)
C(5')	4650(40)	2988(10)	2993(6)	14(3)
C(11')	2620(40)	5053(11)	3197(6)	17(4)
C(24')	5170(40)	1115(11)	3124(6)	17(3)
C(16')	6710(40)	4412(11)	3909(6)	17(4)
C(21')	6300(40)	5354(11)	2892(6)	18(4)

Table 3. Bond lengths [Å] and angles [°] for **7.42**.

Br(1)-C(1)	1.91(2)
O(1)-C(6)	1.22(3)
O(2)-C(6)	1.39(3)
O(2)-C(7)	1.43(2)
C(1)-C(2)	1.39(3)
C(1)-C(24)	1.39(3)
C(9)-C(8)	1.47(3)
C(9)-C(10)	1.49(3)

C(9)-C(22)	1.33(3)
C(17)-H(17A)	0.9700
C(17)-H(17B)	0.9700
C(17)-C(13)	1.53(3)
C(17)-C(18)	1.47(3)
C(5)-H(5)	0.9800
C(5)-C(6)	1.52(3)
C(5)-C(8)	1.53(3)
C(5)-C(4)	1.50(3)
C(14)-C(10)	1.59(3)
C(14)-C(15)	1.57(3)
C(14)-C(13)	1.60(3)
C(14)-C(16)	1.46(3)
C(3)-H(3)	0.9300
C(3)-C(2)	1.45(3)
C(3)-C(4)	1.38(3)
C(2)-H(2)	0.9300
C(21)-H(21A)	0.9700
C(21)-H(21B)	0.9700
C(21)-C(22)	1.50(3)
C(21)-C(12)	1.55(3)
C(19)-H(19)	0.9800
C(19)-C(20)	1.53(3)
C(19)-C(18)	1.54(3)
C(19)-C(12)	1.57(3)
C(8)-H(8A)	0.9700
C(8)-H(8B)	0.9700
C(20)-H(20A)	0.9600
C(20)-H(20B)	0.9600
C(20)-H(20C)	0.9600
C(10)-H(10)	0.9800
C(10)-C(11)	1.57(3)
C(15)-H(15A)	0.9600
C(15)-H(15B)	0.9600
C(15)-H(15C)	0.9600
C(11)-H(11A)	0.9700

C(11)-H(11B)	0.9700
C(11)-C(12)	1.54(3)
C(23)-H(23)	0.9300
C(23)-C(4)	1.47(3)
C(23)-C(24)	1.40(3)
C(13)-H(13)	0.9800
C(13)-C(12)	1.56(3)
C(22)-H(22)	0.9300
C(18)-H(18A)	0.9700
C(18)-H(18B)	0.9700
C(16)-H(16A)	0.9600
C(16)-H(16B)	0.9600
C(16)-H(16C)	0.9600
C(24)-H(24)	0.9300
C(7)-H(7A)	0.9600
C(7)-H(7B)	0.9600
C(7)-H(7C)	0.9600
Br(1')-C(1')	1.91(2)
O(1')-C(6')	1.17(2)
O(2')-C(7')	1.42(3)
O(2')-C(6')	1.32(3)
C(15')-H(15D)	0.9600
C(15')-H(15E)	0.9600
C(15')-H(15F)	0.9600
C(15')-C(14')	1.56(3)
C(23')-H(23')	0.9300
C(23')-C(4')	1.43(3)
C(23')-C(24')	1.37(3)
C(14')-C(13')	1.59(3)
C(14')-C(10')	1.52(3)
C(14')-C(16')	1.51(3)
C(2')-H(2')	0.9300
C(2')-C(1')	1.38(3)
C(2')-C(3')	1.37(3)
C(13')-H(13')	0.9800
C(13')-C(17')	1.52(3)

C(13')-C(12')	1.55(3)
C(17')-H(17C)	0.9700
C(17')-H(17D)	0.9700
C(17')-C(18')	1.58(3)
C(7')-H(7'A)	0.9600
C(7')-H(7'B)	0.9600
C(7')-H(7'C)	0.9600
C(10')-H(10')	0.9800
C(10')-C(9')	1.51(3)
C(10')-C(11')	1.54(3)
C(1')-C(24')	1.35(3)
C(8')-H(8'A)	0.9700
C(8')-H(8'B)	0.9700
C(8')-C(9')	1.51(3)
C(8')-C(5')	1.57(3)
C(4')-C(3')	1.41(3)
C(4')-C(5')	1.48(3)
C(20')-H(20D)	0.9600
C(20')-H(20E)	0.9600
C(20')-H(20F)	0.9600
C(20')-C(19')	1.51(4)
C(9')-C(22')	1.37(3)
C(22')-H(22')	0.9300
C(22')-C(21')	1.47(3)
C(12')-C(19')	1.54(3)
C(12')-C(11')	1.56(3)
C(12')-C(21')	1.59(3)
C(3')-H(3')	0.9300
C(6')-C(5')	1.56(3)
C(19')-H(19')	0.9800
C(19')-C(18')	1.51(3)
C(18')-H(18C)	0.9700
C(18')-H(18D)	0.9700
C(5')-H(5')	0.9800
C(11')-H(11C)	0.9700
C(11')-H(11D)	0.9700

C(24')-H(24')	0.9300
C(16')-H(16D)	0.9600
C(16')-H(16E)	0.9600
C(16')-H(16F)	0.9600
C(21')-H(21C)	0.9700
C(21')-H(21D)	0.9700

C(6)-O(2)-C(7)	112.5(16)
C(2)-C(1)-Br(1)	116.9(17)
C(2)-C(1)-C(24)	124(2)
C(24)-C(1)-Br(1)	118.8(16)
C(8)-C(9)-C(10)	117.7(18)
C(22)-C(9)-C(8)	120.6(19)
C(22)-C(9)-C(10)	121.7(19)
H(17A)-C(17)-H(17B)	108.2
C(13)-C(17)-H(17A)	109.6
C(13)-C(17)-H(17B)	109.6
C(18)-C(17)-H(17A)	109.6
C(18)-C(17)-H(17B)	109.6
C(18)-C(17)-C(13)	110.1(18)
C(6)-C(5)-H(5)	108.8
C(6)-C(5)-C(8)	109.6(17)
C(8)-C(5)-H(5)	108.8
C(4)-C(5)-H(5)	108.8
C(4)-C(5)-C(6)	107.9(17)
C(4)-C(5)-C(8)	113.0(17)
C(15)-C(14)-C(10)	108.5(16)
C(15)-C(14)-C(13)	111.7(16)
C(13)-C(14)-C(10)	100.0(15)
C(16)-C(14)-C(10)	115.4(17)
C(16)-C(14)-C(15)	109.0(16)
C(16)-C(14)-C(13)	112.1(17)
C(2)-C(3)-H(3)	119.8
C(4)-C(3)-H(3)	119.8
C(4)-C(3)-C(2)	120(2)
C(1)-C(2)-C(3)	117(2)

C(1)-C(2)-H(2)	121.7
C(3)-C(2)-H(2)	121.7
H(21A)-C(21)-H(21B)	107.9
C(22)-C(21)-H(21A)	109.2
C(22)-C(21)-H(21B)	109.2
C(22)-C(21)-C(12)	112.1(17)
C(12)-C(21)-H(21A)	109.2
C(12)-C(21)-H(21B)	109.2
O(1)-C(6)-O(2)	124.2(18)
O(1)-C(6)-C(5)	124.7(19)
O(2)-C(6)-C(5)	111.1(17)
C(20)-C(19)-H(19)	109.8
C(20)-C(19)-C(18)	109.7(19)
C(20)-C(19)-C(12)	115.7(18)
C(18)-C(19)-H(19)	109.8
C(18)-C(19)-C(12)	101.7(17)
C(12)-C(19)-H(19)	109.8
C(9)-C(8)-C(5)	117.1(18)
C(9)-C(8)-H(8A)	108.0
C(9)-C(8)-H(8B)	108.0
C(5)-C(8)-H(8A)	108.0
C(5)-C(8)-H(8B)	108.0
H(8A)-C(8)-H(8B)	107.3
C(19)-C(20)-H(20A)	109.5
C(19)-C(20)-H(20B)	109.5
C(19)-C(20)-H(20C)	109.5
H(20A)-C(20)-H(20B)	109.5
H(20A)-C(20)-H(20C)	109.5
H(20B)-C(20)-H(20C)	109.5
C(9)-C(10)-C(14)	112.6(16)
C(9)-C(10)-H(10)	111.0
C(9)-C(10)-C(11)	107.8(16)
C(14)-C(10)-H(10)	111.0
C(11)-C(10)-C(14)	103.1(16)
C(11)-C(10)-H(10)	111.0
C(14)-C(15)-H(15A)	109.5

C(14)-C(15)-H(15B)	109.5
C(14)-C(15)-H(15C)	109.5
H(15A)-C(15)-H(15B)	109.5
H(15A)-C(15)-H(15C)	109.5
H(15B)-C(15)-H(15C)	109.5
C(10)-C(11)-H(11A)	112.1
C(10)-C(11)-H(11B)	112.1
H(11A)-C(11)-H(11B)	109.7
C(12)-C(11)-C(10)	98.6(16)
C(12)-C(11)-H(11A)	112.1
C(12)-C(11)-H(11B)	112.1
C(4)-C(23)-H(23)	121.1
C(24)-C(23)-H(23)	121.1
C(24)-C(23)-C(4)	118(2)
C(17)-C(13)-C(14)	120.3(17)
C(17)-C(13)-H(13)	108.7
C(17)-C(13)-C(12)	102.7(17)
C(14)-C(13)-H(13)	108.7
C(12)-C(13)-C(14)	107.0(16)
C(12)-C(13)-H(13)	108.7
C(9)-C(22)-C(21)	121.5(19)
C(9)-C(22)-H(22)	119.3
C(21)-C(22)-H(22)	119.3
C(3)-C(4)-C(5)	121(2)
C(3)-C(4)-C(23)	121(2)
C(23)-C(4)-C(5)	117.6(19)
C(17)-C(18)-C(19)	102.3(18)
C(17)-C(18)-H(18A)	111.3
C(17)-C(18)-H(18B)	111.3
C(19)-C(18)-H(18A)	111.3
C(19)-C(18)-H(18B)	111.3
H(18A)-C(18)-H(18B)	109.2
C(14)-C(16)-H(16A)	109.5
C(14)-C(16)-H(16B)	109.5
C(14)-C(16)-H(16C)	109.5
H(16A)-C(16)-H(16B)	109.5

H(16A)-C(16)-H(16C)	109.5
H(16B)-C(16)-H(16C)	109.5
C(1)-C(24)-H(24)	120.1
C(23)-C(24)-C(1)	120(2)
C(23)-C(24)-H(24)	120.1
O(2)-C(7)-H(7A)	109.5
O(2)-C(7)-H(7B)	109.5
O(2)-C(7)-H(7C)	109.5
H(7A)-C(7)-H(7B)	109.5
H(7A)-C(7)-H(7C)	109.5
H(7B)-C(7)-H(7C)	109.5
C(21)-C(12)-C(19)	113.9(17)
C(21)-C(12)-C(13)	110.8(17)
C(11)-C(12)-C(21)	106.9(16)
C(11)-C(12)-C(19)	113.4(17)
C(11)-C(12)-C(13)	105.5(16)
C(13)-C(12)-C(19)	106.0(16)
C(6')-O(2')-C(7')	115.4(17)
H(15D)-C(15')-H(15E)	109.5
H(15D)-C(15')-H(15F)	109.5
H(15E)-C(15')-H(15F)	109.5
C(14')-C(15')-H(15D)	109.5
C(14')-C(15')-H(15E)	109.5
C(14')-C(15')-H(15F)	109.5
C(4')-C(23')-H(23')	119.8
C(24')-C(23')-H(23')	119.8
C(24')-C(23')-C(4')	120(2)
C(15')-C(14')-C(13')	114.0(18)
C(10')-C(14')-C(15')	110.2(17)
C(10')-C(14')-C(13')	103.1(16)
C(16')-C(14')-C(15')	105.7(17)
C(16')-C(14')-C(13')	111.1(17)
C(16')-C(14')-C(10')	112.9(18)
C(1')-C(2')-H(2')	121.6
C(3')-C(2')-H(2')	121.6
C(3')-C(2')-C(1')	117(2)

C(14')-C(13')-H(13')	110.2
C(17')-C(13')-C(14')	116.3(18)
C(17')-C(13')-H(13')	110.2
C(17')-C(13')-C(12')	104.6(18)
C(12')-C(13')-C(14')	104.8(16)
C(12')-C(13')-H(13')	110.2
C(13')-C(17')-H(17C)	110.7
C(13')-C(17')-H(17D)	110.7
C(13')-C(17')-C(18')	105.4(19)
H(17C)-C(17')-H(17D)	108.8
C(18')-C(17')-H(17C)	110.7
C(18')-C(17')-H(17D)	110.7
O(2')-C(7')-H(7'A)	109.5
O(2')-C(7')-H(7'B)	109.5
O(2')-C(7')-H(7'C)	109.5
H(7'A)-C(7')-H(7'B)	109.5
H(7'A)-C(7')-H(7'C)	109.5
H(7'B)-C(7')-H(7'C)	109.5
C(14')-C(10')-H(10')	110.7
C(14')-C(10')-C(11')	102.0(17)
C(9')-C(10')-C(14')	112.0(17)
C(9')-C(10')-H(10')	110.7
C(9')-C(10')-C(11')	110.5(17)
C(11')-C(10')-H(10')	110.7
C(2')-C(1')-Br(1')	116.8(16)
C(24')-C(1')-Br(1')	120.5(17)
C(24')-C(1')-C(2')	123(2)
H(8'A)-C(8')-H(8'B)	107.6
C(9')-C(8')-H(8'A)	108.7
C(9')-C(8')-H(8'B)	108.8
C(9')-C(8')-C(5')	114.0(19)
C(5')-C(8')-H(8'A)	108.8
C(5')-C(8')-H(8'B)	108.8
C(23')-C(4')-C(5')	120.9(19)
C(3')-C(4')-C(23')	115.5(19)
C(3')-C(4')-C(5')	123.6(19)

H(20D)-C(20')-H(20E)	109.5
H(20D)-C(20')-H(20F)	109.5
H(20E)-C(20')-H(20F)	109.5
C(19')-C(20')-H(20D)	109.5
C(19')-C(20')-H(20E)	109.5
C(19')-C(20')-H(20F)	109.5
C(8')-C(9')-C(10')	122.1(19)
C(22')-C(9')-C(10')	118(2)
C(22')-C(9')-C(8')	120(2)
C(9')-C(22')-H(22')	117.9
C(9')-C(22')-C(21')	124(2)
C(21')-C(22')-H(22')	118.0
C(13')-C(12')-C(11')	104.5(17)
C(13')-C(12')-C(21')	110.9(17)
C(19')-C(12')-C(13')	108.4(19)
C(19')-C(12')-C(11')	113.6(18)
C(19')-C(12')-C(21')	115.5(19)
C(11')-C(12')-C(21')	103.4(17)
C(2')-C(3')-C(4')	124(2)
C(2')-C(3')-H(3')	118.1
C(4')-C(3')-H(3')	118.1
O(1')-C(6')-O(2')	127(2)
O(1')-C(6')-C(5')	123(2)
O(2')-C(6')-C(5')	110.2(17)
C(20')-C(19')-C(12')	114(2)
C(20')-C(19')-H(19')	110.3
C(12')-C(19')-H(19')	110.3
C(18')-C(19')-C(20')	111(2)
C(18')-C(19')-C(12')	100.7(19)
C(18')-C(19')-H(19')	110.3
C(17')-C(18')-H(18C)	110.8
C(17')-C(18')-H(18D)	110.9
C(19')-C(18')-C(17')	104.5(19)
C(19')-C(18')-H(18C)	110.8
C(19')-C(18')-H(18D)	110.8
H(18C)-C(18')-H(18D)	108.9

C(8')-C(5')-H(5')	109.6
C(4')-C(5')-C(8')	110.3(17)
C(4')-C(5')-C(6')	107.8(18)
C(4')-C(5')-H(5')	109.6
C(6')-C(5')-C(8')	109.9(17)
C(6')-C(5')-H(5')	109.6
C(10')-C(11')-C(12')	99.6(17)
C(10')-C(11')-H(11C)	111.8
C(10')-C(11')-H(11D)	111.8
C(12')-C(11')-H(11C)	111.9
C(12')-C(11')-H(11D)	111.9
H(11C)-C(11')-H(11D)	109.6
C(23')-C(24')-H(24')	119.6
C(1')-C(24')-C(23')	121(2)
C(1')-C(24')-H(24')	119.6
C(14')-C(16')-H(16D)	109.5
C(14')-C(16')-H(16E)	109.5
C(14')-C(16')-H(16F)	109.5
H(16D)-C(16')-H(16E)	109.5
H(16D)-C(16')-H(16F)	109.5
H(16E)-C(16')-H(16F)	109.5
C(22')-C(21')-C(12')	112.1(19)
C(22')-C(21')-H(21C)	109.2
C(22')-C(21')-H(21D)	109.2
C(12')-C(21')-H(21C)	109.2
C(12')-C(21')-H(21D)	109.2
H(21C)-C(21')-H(21D)	107.9

Symmetry transformations used to generate equivalent atoms:

Table 4. Anisotropic displacement parameters ($Å^2 x\ 10^3$) for **7.42**. The anisotropic displacement factor exponent takes the form: $-2p^2[\ h^2\ a^{*2}U^{11} + ... + 2\ h\ k\ a^*\ b^*\ U^{12}\ ]$

	U^{11}	U^{22}	U^{33}	U^{23}	U^{13}	U^{12}

Br(1)	41(1)	18(1)	19(1)	0(1)	2(1)	2(1)
O(1)	11(5)	38(9)	12(5)	-1(5)	-2(4)	-5(5)
O(2)	9(4)	24(6)	14(5)	2(4)	-2(3)	-2(3)
C(1)	23(7)	18(5)	19(9)	1(5)	6(6)	4(4)
C(9)	8(6)	18(5)	12(5)	1(4)	-1(5)	0(4)
C(17)	29(10)	20(5)	17(6)	6(5)	-7(6)	-4(6)
C(5)	12(6)	18(4)	11(5)	1(3)	-2(4)	1(3)
C(14)	11(4)	14(4)	11(3)	1(3)	0(3)	3(3)
C(3)	20(5)	26(8)	12(9)	0(7)	-1(6)	-4(5)
C(2)	24(8)	11(7)	26(10)	1(6)	11(7)	0(5)
C(21)	14(6)	11(5)	8(6)	-2(4)	-1(5)	-3(4)
C(6)	10(3)	12(4)	11(3)	0(2)	-2(2)	0(2)
C(19)	16(9)	17(5)	13(6)	2(4)	-3(5)	-2(5)
C(8)	13(6)	19(5)	18(8)	2(4)	-3(6)	1(4)
C(20)	25(7)	25(7)	24(7)	-1(6)	4(6)	-2(6)
C(10)	10(3)	13(3)	11(3)	1(2)	-1(2)	0(2)
C(15)	14(5)	16(5)	15(5)	-1(4)	3(4)	1(4)
C(11)	14(5)	18(5)	15(5)	-1(4)	-3(4)	1(4)
C(23)	22(6)	17(5)	12(7)	6(4)	1(6)	5(4)
C(13)	10(5)	17(4)	10(4)	1(3)	1(4)	2(4)
C(22)	9(4)	10(4)	9(4)	0(2)	-1(2)	-1(2)
C(4)	16(4)	16(3)	15(4)	0(2)	-1(2)	0(2)
C(18)	23(8)	19(6)	13(6)	4(5)	-1(6)	-3(6)
C(16)	14(6)	21(9)	10(8)	1(7)	0(5)	0(6)
C(24)	22(6)	17(5)	17(8)	4(5)	3(6)	5(4)
C(7)	15(11)	42(14)	15(6)	-2(5)	-4(5)	5(10)
C(12)	12(5)	16(4)	11(4)	2(3)	-1(4)	-1(3)
Br(1')	50(2)	18(1)	28(1)	2(1)	-6(1)	6(1)
O(1')	8(6)	31(8)	8(6)	7(6)	1(5)	-1(5)
O(2')	13(5)	21(7)	14(6)	5(5)	2(4)	-4(5)
C(15')	9(7)	31(11)	12(7)	-3(7)	1(6)	0(6)
C(23')	18(5)	18(4)	13(6)	3(4)	-1(4)	-2(3)
C(14')	9(6)	22(5)	10(5)	0(4)	0(4)	1(4)
C(2')	18(5)	14(4)	9(6)	-1(3)	0(4)	0(3)
C(13')	14(6)	23(5)	14(5)	3(4)	-4(5)	0(4)

C(17')	26(9)	26(6)	18(6)	2(4)	-3(5)	4(5)
C(7')	21(9)	26(11)	13(6)	-2(6)	0(6)	6(8)
C(10')	11(6)	23(7)	13(5)	-2(5)	-1(5)	0(5)
C(1')	22(5)	17(4)	14(8)	3(4)	-1(5)	-2(3)
C(8')	20(7)	20(5)	20(10)	-3(4)	0(7)	-1(4)
C(4')	17(5)	17(4)	13(8)	2(3)	4(5)	1(3)
C(20')	33(11)	42(11)	30(14)	12(10)	-1(9)	3(10)
C(9')	14(5)	20(4)	14(5)	-3(4)	0(4)	-1(4)
C(22')	17(7)	26(5)	19(7)	1(5)	2(7)	-1(5)
C(12')	13(7)	26(6)	14(5)	5(4)	-3(4)	2(5)
C(3')	17(6)	14(5)	13(8)	0(4)	4(6)	0(4)
C(6')	13(5)	25(10)	10(5)	5(5)	3(4)	-2(5)
C(19')	26(9)	30(6)	21(6)	5(4)	-3(5)	9(6)
C(18')	25(8)	27(7)	21(6)	5(5)	-2(6)	4(7)
C(5')	15(5)	16(4)	10(5)	1(4)	3(4)	1(4)
C(11')	16(6)	19(7)	17(7)	-1(5)	1(5)	4(5)
C(24')	21(5)	17(4)	12(6)	4(4)	-1(4)	-2(3)
C(16')	9(6)	28(9)	14(9)	3(7)	0(6)	2(6)
C(21')	14(8)	26(6)	14(6)	2(4)	-3(5)	-2(5)

Table 5. Hydrogen coordinates (x 10^4) and isotropic displacement parameters ($Å^2$x 10^3) for **7.42**.

	x	y	z	U(eq)
H(17A)	1654	7185	83	27
H(17B)	-318	7434	344	27
H(5)	4079	3986	593	16
H(3)	-831	3015	879	24
H(2)	-1663	1902	662	24
H(21A)	543	6096	1334	13
H(21B)	-1540	6241	1071	13
H(19)	3614	7149	1096	18
H(8A)	318	4279	391	20
H(8B)	-675	4146	777	20
H(20A)	762	7983	1169	37
H(20B)	-211	7314	1334	37
H(20C)	-1048	7554	952	37
H(10)	4006	5109	437	14
H(15A)	5002	6202	94	23
H(15B)	3146	6461	-183	23
H(15C)	4075	5722	-209	23
H(11A)	4321	5770	1017	19
H(11B)	5123	6194	676	19
H(23)	5309	2988	323	20
H(13)	-1088	6385	458	15
H(22)	-1183	5035	1145	12
H(18A)	2734	7948	579	22
H(18B)	4421	7341	494	22
H(16A)	485	5069	-84	23
H(16B)	-517	5764	-208	23
H(16C)	-1470	5420	143	23
H(24)	4581	1870	160	23
H(7A)	7690	4090	1599	36
H(7B)	6211	3436	1651	36
H(7C)	5041	4142	1696	36

H(15D)	3495	4976	4245	26
H(15E)	1974	4463	4027	26
H(15F)	1793	5233	3944	26
H(23')	2889	1834	3252	19
H(2')	9936	1382	2683	16
H(13')	7450	5488	3555	21
H(17C)	6343	6430	3817	28
H(17D)	4475	6004	4029	28
H(7'A)	734	2952	2062	30
H(7'B)	2274	3601	2069	30
H(7'C)	-313	3630	2202	30
H(10')	2778	4112	3451	19
H(8'A)	6803	3338	3406	24
H(8'B)	7952	3421	3025	24
H(20D)	6991	6707	3153	52
H(20E)	5068	7258	3105	52
H(20F)	5672	6774	2784	52
H(22')	8013	4465	2767	25
H(3')	8493	2457	2689	18
H(19')	2324	6338	3018	31
H(18C)	1544	6261	3618	29
H(18D)	2966	6939	3606	29
H(5')	3230	2999	3140	17
H(11C)	1254	5200	3331	21
H(11D)	2170	4937	2953	21
H(24')	4324	764	3226	20
H(16D)	6345	4360	4161	25
H(16E)	8156	4647	3884	25
H(16F)	6828	3978	3798	25
H(21C)	5577	5440	2660	22
H(21D)	7726	5613	2903	22