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Bo Cheng

Enantiomeric Scaffolds.
Molybdenum Pyranyl π-Complexes for the Asymmetric Construction of Oxa-Heterocycles

By

Bo Cheng
Doctor of Philosophy

Department of Chemistry

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By

Bo Cheng
M.S., University of Science and Technology of China, 2004
B.E., Tianjin University, 1999

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An Abstract of
A dissertation submitted to the Faculty of the Graduate School of
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Department of Chemistry

2008

Abstract

Enantiomerically pure TpMo(CO)$_2$(η^3-pyranyl) complexes have proven to be excellent enantiomeric organometallic scaffolds for the asymmetric construction of structurally diverse oxygen-containing heterocyclic systems. Chiral, non-racemic η^3-(2,3,4)-2-methyl-5-oxopyranyl molybdenum scaffold was prepared with high enantiopurity. An improved method was developed for the synthesis of chiral, non-racemic η^3-(2,3,4)-5-oxopyranyl molybdenum scaffold.

Neutral TpMo(CO)$_2$(η^3-pyranyl) scaffolds bearing an internal alkoxide can undergo a novel intramolecular '1,5-Michael-like' reaction. Through a one-pot '1,5-Michael-demetalation' sequence, the 6,8-dioxabicyclo[3.2.1]oct-3-en-2-one frame work can be rapidly accessed in good to excellent yields with high enantiopurity. An enantiocontrolled total synthesis of (+)-(1*R*,2*S*,5*S*,7*R*)-2-hydroxy-*exo*-brevicomin was completed utilizing the intramolecular '1,5-Michael-demetalation' cascade.

Solid sodium methoxide participates in an unprecedented intermolecular '1,5-Michael-like' reaction with neutral TpMo(CO)$_2$(5-oxo-η^3-pyranyl) complexes with complete regio- and stereocontrol. The resulting dimethoxy complexes lead to the formation of various 2,2,6-trisubstituted and 2,6-*trans* disubstituted pyranyl molybdenum complexes. The synthetic potential of this methodology was demonstrated by the synthesis of (2*S*,6*R*)-2,6-dially-2-ethyl-2*H*-pyranone and (2*R*,6*S*)-2-ethyl-6-phenyl-pyranone.

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To my parents

Without you, I would not even think I could make it.

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List of Abbreviations

[α]	specific rotation
Ac	acetyl
anal.	analysis
Aq	aqueous
Ar	argon
Bn	benzyl
br	broad
bu	butyl
^{o}C	degree Celsius
calcd	calculated
CAN	ceric ammonium nitrate
Cbz	benzyloxycarbonyl
Cy	cyclohexyl
δ	chemical shift(s)
d	doublet
DEAD	diethyl azodicarboxylate
DMAP	dimethylamino pyridine
DME	1,2-dimethoxylethane
Decomp	decomposed
DMSO	dimethyl sulfoxide
E	entgegen
ee	enantiomeric excess
ESI	electrospray ionization
Et	ethyl
FAB	fast atom bombardment
FT	Fourier transform
g	gram(s)
h	hour(s)
HPLC	high performance liquid chromatography
HRMS	high resolution mass spectroscopy
Hz	hertz
IR	Infrared Spectroscopy
i	iso
J	coupling constant
LA	Lewis acid
LDA	lithium diisopropylamide
LiHMDS	lithium bis(trimethylsilyl)amide
mol	mole

m	multiplet
m	meta
m-CPBA	*meta*-chloroperbenzoic acid
Me	methyl
mg	milligram(s)
MHz	megahertz
min	minute(s)
mL	milliliter(s)
μL	microliter(s)
mmol	millimole(s)
mp	melting point
NMR	nuclear magnetic resonance
NMO	N-methylmorpholine oxide
NOE	nuclear Overhauser effect
nm	nanometer(s)
Ns	2-nitrobenzenesulfonyl
PG	protecting group
Ph	phenyl
ppm	parts per million
pr	propyl
py	pyridine
q	quartet
R_f	retention factor
rt	room temperature
s	singlet
t	triplet
t	tertiary
TBME	*tert*-butyl methyl ether
TBS	*tert*-butyl dimethyl silyl
TFA	trifluoroacetic acid
THF	tetrahydrofuran
TIPS	triisopropylsilyl
TLC	thin layer chromatography
Tp	hydridotris(1-pyrazolyl)borate
Tr	triphenylcarbenium
UV	ultraviolet
Z	zusammen

Chapter 1

Application of Stoichiometric Transition Metal Complexes in Organic Synthesis

Introduction

In recent decades transition metal complexes have served as one of the most important categories of reagents in organic reaction in both catalytic and stoichiometric manner. Although considerable attention is drawn to catalytic processes, applications of stoichiometric transition metal complexes in the synthesis of complex organic molecules have made significant progress lately.[1] Especially with the development of various approaches to prepare enantiomerically pure organometallic complexes,[2] stoichiometric transition metal complexes become exceptionally valuable for the enantiocontrolled bond constructions. This chapter mainly focuses on recent applications of stoichiometric transition metal complexes in complex organic molecule synthesis, particularly in the area of natural product synthesis. Only six most commonly used stoichiometric transition metal species, zirconium, chromium, molybdenum, tungsten, cobalt and iron complexes are covered in this literature review.

Zirconium Complexes

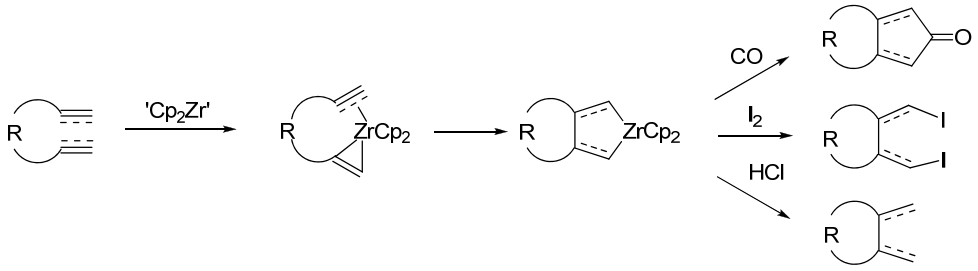
Zirconium complexes can undergo useful coupling of alkenes and alkynes *via*

[1] For recent reviews, see: (a) Fairlamb, I. J. S. *Annu, Pre. Prog. Chem., Sect. B* **2003**, *99*, 138-160. (b) Fratt, R.; Christie, S. D. R. *J. Chem. Soc., Perkin Trans.1* **2002**, 447-458. (c) Fletcher, A. J.; Christie, S. D. *J. Chem. Soc.*, *Perkin Trans.1* **2001**, 1-13. (d) Lloyd-Jones, G. C.; Fairlamb, I. J. S. *Annu, Pre. Prog. Chem., Sect. B*, **2001**, *97*, 113-141. (e) Comely, A. C.; Gibson, S. E.; Sur, S. *J. Chem. Soc., Perkin Trans.1* **2000**, 109-124. (f) Li, C. -L.; Liu, R. -S. *Chem. Rev.* **2000**, *100*, 3127-3162. (g) Comely, A. C.; Gibson, S. E. *J. Chem. Soc., Perkin Trans.1*, **1999**, 223-228. (h) Donohoe, T. J.; Harji, R. R.; Moore, P. R.; Waring, M. J. *J. Chem. Soc., Perkin Trans.1* **1998**, 819-834. (i) Blagg, J. *Contemp. Org. Synth.* **1995**, *2*, 43-64.

[2] For a recent review, see: Paley, R. S. *Chem. Rev*. **2002**, *102*, 1493-1523.

zirconocene (Cp_2Zr) complexes.[3] The resulting five-membered zirconacycles can be converted into various highly functionalized carbocycles and heterocycles by different cleavage paths. Pioneered by Negishi,[4] the intramolecular enyne, dinyl and diene cyclizations mediated by zirconocene (Scheme 1) have been widely utilized in complex organic synthesis.

Scheme 1. Intramolecular Enyne, Dinyl and Diene Cyclizations Mediated by Zirconocene

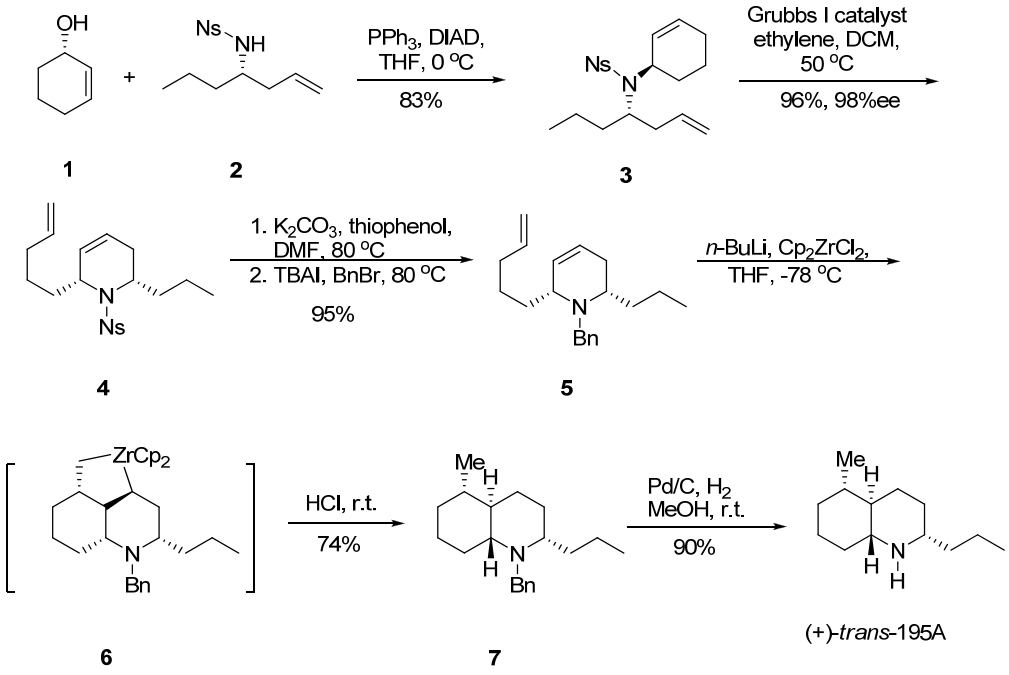


Alkaloid *trans*-195A was isolated from the skin of dendrobatid frogs, and only very limited amounts are available from natural sources. In 2005, Blechert reported the total synthesis of (+)-*trans*-195A *via* a zirconium-mediated intramolecular diene cyclization (Scheme 2).[5] Mitsunobu reaction of allylic alcohol **1** and compound **2** afforded amine **3**. Ring-rearrangement metathesis of **4** with 5 mol % Grubbs I catalyst provided 2,6-*cis*-disubstituted tetrahydropyridine derivative **5** in 96% yield and 98% ee. After changing the nitrogen protecting group, cyclization reaction of **5** was carried out with

[3] For reviews, see: (a) Negishi, E.; Takahashi, T. *Acc. Chem. Res.* **1994**, *27*, 124-130. (b) Broene, R. D.; Buchwald, S. L. *Science* **1993**, *261*, 1696-1701.
[4] (a) Negishi, E.; Cederbaum, F. E.; Takahashi, T. *Tetrahedron Lett*. **1986**, *25*, 2829-2832. (b) Negishi, E.; Swanson,D. R.; Cederbaum, F. E.; Takahashi, T. *Tetrahedron Lett*. **1987**, *9*, 917-920. (c) Rousset, C. J.; Swanson, D. R.; Lamaty, F.; Negishi, E. *Tetrahedron Lett*. **1989**, *38*, 5105-5108.
[5] Holub, N.; Neidhöfer, J.; Blecher, S. *Org. Lett*. **2005**, *7*, 1227-1229.

*n*BuLi and Cp_2ZrCl_2 to afforded bicyclic **7** in 74% yield, which went through zirconacycle intermediate **6**. Final deprotection with Pd-C/H_2 afforded (+)-*trans*-195A in 90% yield.

Scheme 2. Total synthesis of (+)-*trans*-195A *via* a Zirconium-mediated Intramolecular Diene Cyclization

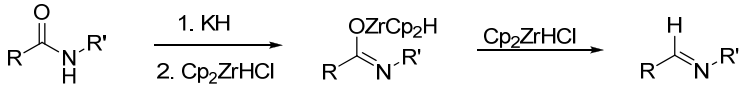


Cp_2ZrHCl, also known as 'Schwartz's reagent',[6] is well known for the hydrozirconation reaction. In 1996, Ganem developed an approach for reduction of a carboxyamide to an imine in one step with Cp_2ZrHCl as shown in Scheme 3.[7] First, amide **8** was transformed to hydridozirconocene **9** by KH metalation followed by treatment of Cp_2ZrHCl. Although experiments indicated another equivalent of Cp_2ZrHCl was required for the reduction of

[6] (a) Schwartz, J.; Labinger, J. A. *Angew. Chem., Int. Ed. Engl.* **1976**, *15*, 333-340. (b) For a brief review, see: Eduardo, F-M. *Synlett* **1999**, *7*, 1179.
[7] Schedler, D. J. A.; Li, J.; Ganem, B. *J. Org. Chem.* **1996**, *61*, 4115-4119.

9 to the final imine **10**, the mechanism was still unclear.

Scheme 3. Reduction of Carboxyamide to Imine with Cp_2ZrHCl

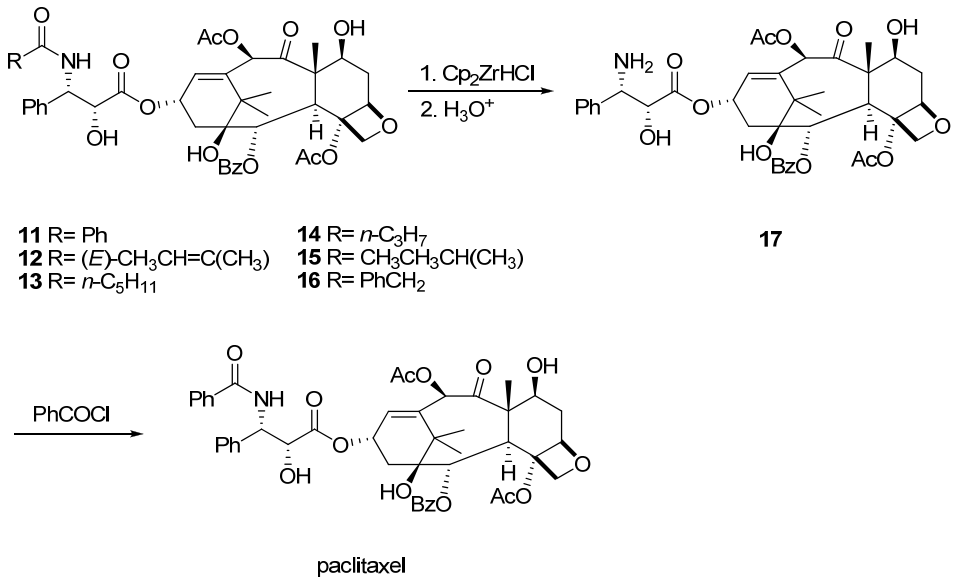


8 **9** **10**

This novel deoxygenation method was utilized in the synthesis of paclitaxel which is potent against ovarian and breast cancer in human clinical trial.[8] Paclitaxel can be extracted in very limited amount from pacific yew. In contrast, six primary taxane constituents **11**-**16** (Scheme 4) that share the identical tetracyclic core structure with paclitaxel can be obtained in substantial quantities from ornamental yew trees. Utilizing this one step carboxyamide to imine reduction with Cp_2ZrHCl, Natural Pharmaceuticals, Inc. developed and implemented a highly convergent commercial synthesis of paclitaxel[8] from taxane constituents **11**-**16** (Scheme 4). With this approach, the cost of synthesis of large scale high-purity paclitaxel is reduced dramatically compared to extraction from pacific yew.

[8] Ganem, B.; Franke, R. R. *J. Org. Chem.* **2007**, *72*, 3981-3987.

Scheme 4. Total Synthesis of Paclitaxel *via* Cp_2ZrHCl-mediated Reduction



11 R= Ph
12 R= (*E*)-CH_3CH=$C(CH_3)$
13 R= *n*-C_5H_{11}
14 R= *n*-C_3H_7
15 R= $CH_3CH_3CH(CH_3)$
16 R= $PhCH_2$

17

Chromium complexes

Two stoichiometric forms of chromium complexes are well studied: chromium Fischer carbene complexes[9] and η^6-$Cr(CO)_3$-arene complexes.[10] The Dötz benzannulation reaction[11] is one of the best-known reactions of chromium carbenes since its discovery[12] in 1975. In this type of reaction, an α,β-unsaturated pentacarbonyl chromium carbene complex reacts with an alkyne to afford a substituted hydroquinone derivative. In 2005 Pulley reported the synthesis of (*S*,*S*)-isodityrosine *via* the Dötz benzannulation (Scheme

[9] For reviews, see: (a) Barluenga, J.; Fermandez-Rodriguez, M. A.; Aguilar, E. *J. Organomet. Chem.* **2005**, *690*, 539-587. (b) Barbuenga, J.; Santamaria, J.; Tomas, M. *Chem. Rev.* **2004**, *104*, 2259-2283. (c) De Meijere, A.; Schirmer, H.; Duetsch, M. *Angew. Chem., Int. Ed. Engl.* **2000**, *39*, 3964-4002. (d) Wulff, W. D. *Organometallics* **1998**, *17*, 3116-3134.

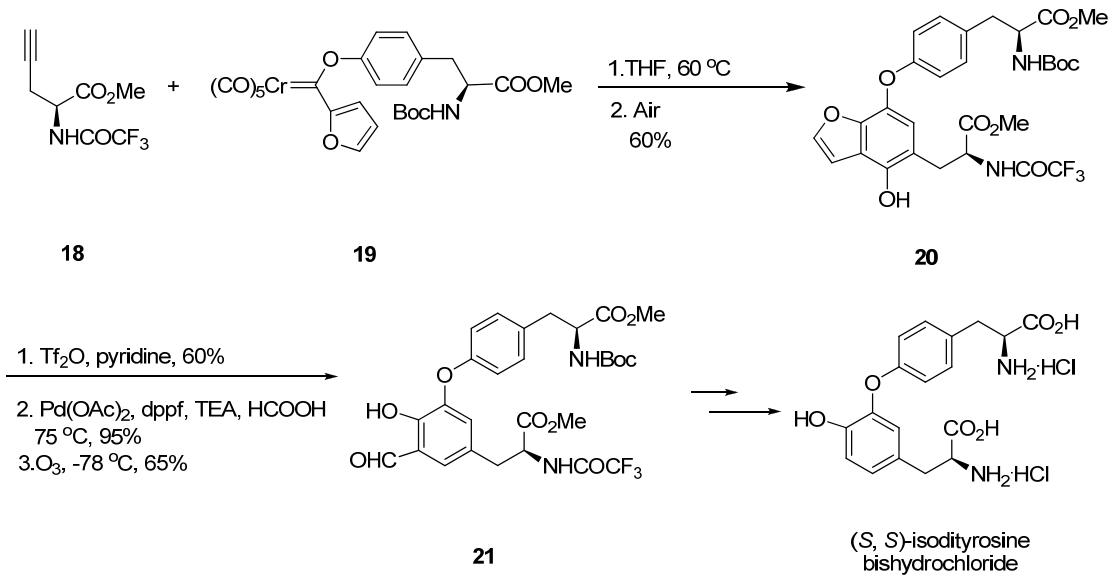
[10] For a recent review on (arene)$Cr(CO)_3$ complexes, see: Marta, R.; Gema, D.; Javier, P-C. *Chem. Soc. Rev.* **2007**, *36*, 1589-1604.

[11] For reviews, see: (a) Dötz, K. H.; Wenzel, B.; Jahr, H. C. In *Topics in Current Chemistry,* Schalley, C. A.; Vögtle, F.; Dötz, K. H., Eds.; Springer: Berlin/Heidelberg, 2004; Vol 248, p 68-80. (b) Dötz, K. H.; Tomuschat, P. *Chem. Soc. Rev.* **1999**, *28*, 187-198.

[12] Dötz, K. H. *Angew. Chem., Int. Ed. Engl.* **1975**, *14*, 644-645.

5).[13] Carbene complex **19** was subjected to benzannulation in the presence of alkyne **18** at 60 °C. Exposure of the reaction mixture to air oxidized the coordinated chromium, and afforded diaryl ether **20** in 60% yield. After 7 more steps, compound **20** was converted to (*S*,*S*)-isodityrosine bishydrochloride which is the key structure of a large class of biologically active natural products containing an endocyclic diaryl ether.[14]

Scheme 5. Synthesis of (*S*,*S*)-Isodityrosine by Dötz Benzannulation

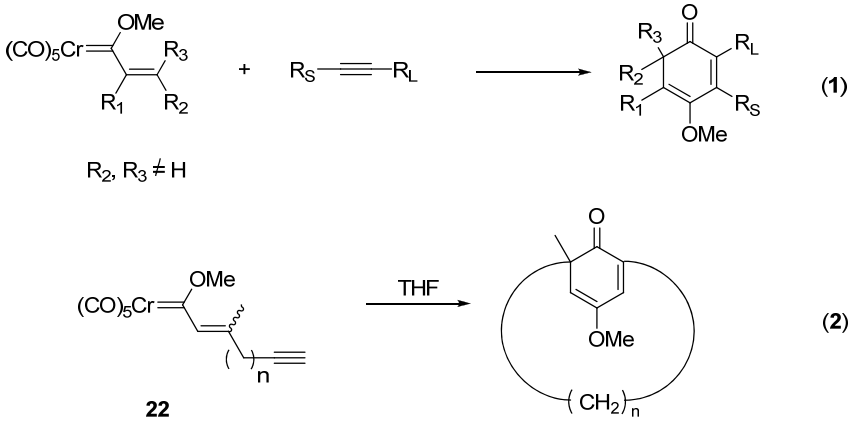


As a variant of previously described benzannulation, in 1984, Wulff reported cyclohexadinone annulation[15] *via* Fischer chromium carbene complexes where both substituents of the β-carbon are non-hydrogen (Scheme 6, eq 1). This method allows a rapid construction of cyclohexadienones bearing a quaternary carbon center. Later in

[13] Gupta, A.; Sen, S.; Harmata, M.; Pulley, S. R. *J. Org. Chem.* **2005**, *70*, 7422-7425.
[14] Fry, S. C. *Biochem. J.* **1982**, *204*, 449-455.
[15] Tang, P-C.; Wulff, W. D. *J. Am. Chem. Soc*. **1984**, *106*, 1132-1133.

2007, he extended this methodology to an intramolecular cyclohexadienone annulation[16] of chromium carbene complexes **22**, and applied it to synthesis of macrocycles possessing a highly substituted (including a quaternary carbon center) cyclohexane core structure (Scheme 6, eq 2).

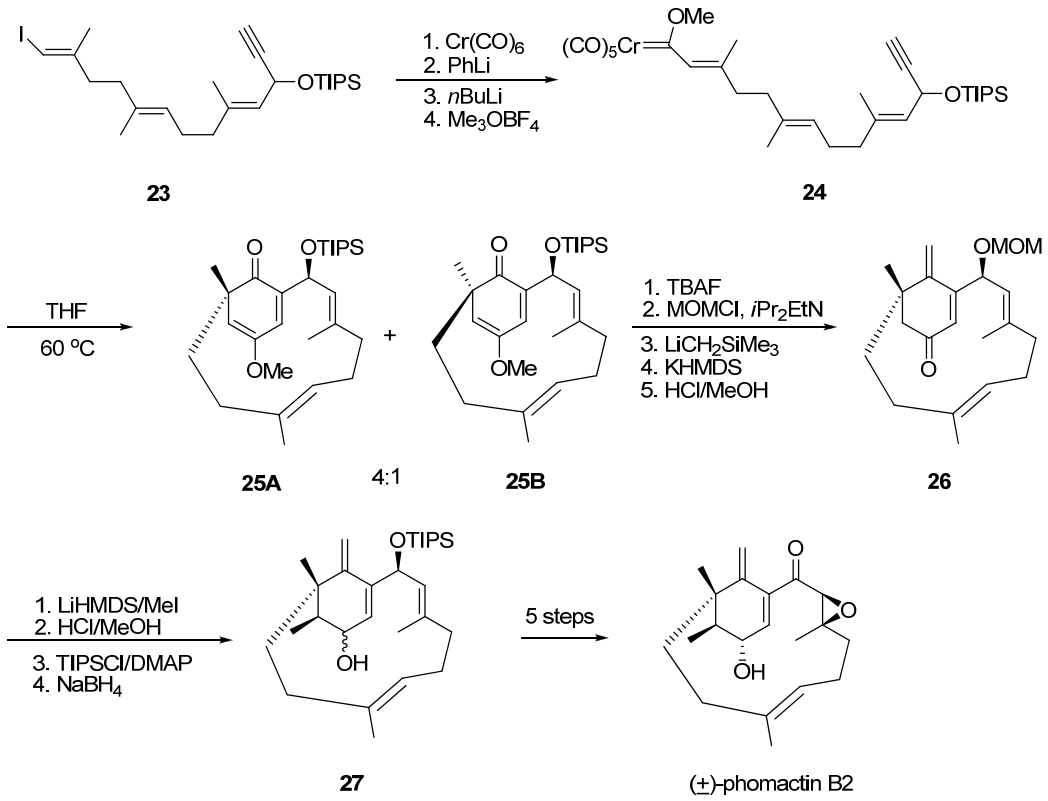
Scheme 6. Cyclohexadienone Annulation



Shown in Scheme 7, in 2007 Wulff completed the total synthesis of (±)-phomactin B2[17] *via* the intramolecular cyclohexadienone annulation of chromium carbene complex **24** which was prepared from **23** by Fischer method. The intramolecular cyclohexadienone annulation of **24** gave a mixture of diastereomer **25A** and **25B** in a 4:1 ratio. After protecting group exchange and installation of the exocyclic double bond, methylation of the enolate of **26** afforded **27** as a single diastereomer with the methyl group *anti* to the macrocyclic tether. Substrate **27** was converted to (±)-phomactin after 5 additional steps.

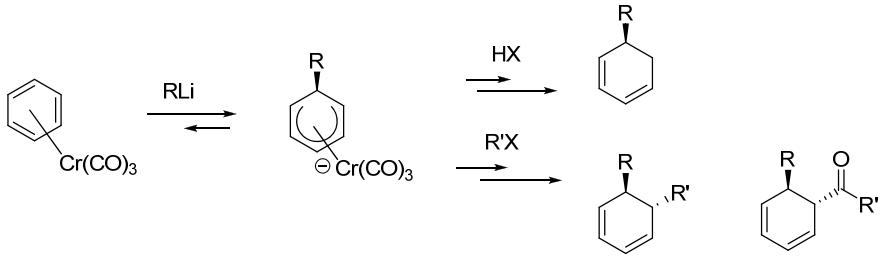
[16] Huang, J.; Wang, H.; Wu, C.; Wulff, W. D. *Org. Lett*. **2007**, *9*, 2799-2802.
[17] Huang, J.; Wu, C.; Wulff, W. D. *J. Am. Chem. Soc*. **2007**, *129*, 13366-13367.

Scheme 7. Total Synthesis of (±)-Phomactin B2 via an Intramolecular Cyclohexadienone Annulation of a Chromium Carbene Complex



η^6-$Cr(CO)_3$-arene complexes are widely used in dearomatization reactions, and provide an efficient route to various substituted cyclohexadienes (Scheme 8).[18]

Scheme 8. Tricarbonylchromium-mediated Dearomatization

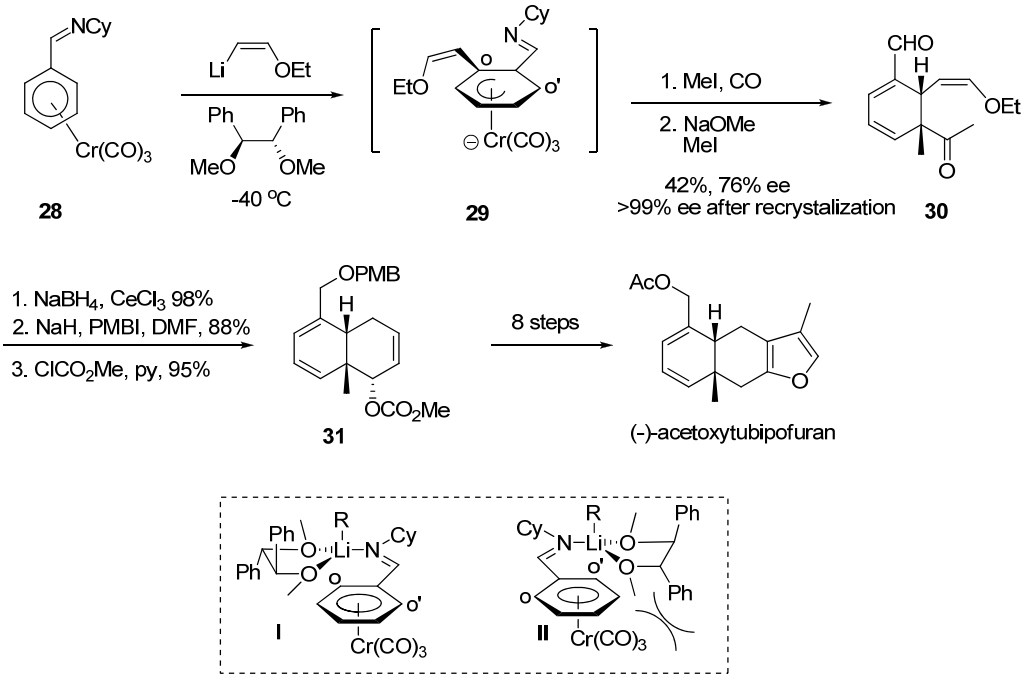


[18] For review, see: Pape, A.; Kaliappan, K.; Kündig, E. P. *Chem. Rev.* **2000**, *100*, 2917-2940.

In 2003, an enantioselective *ortho*-nucleophilic addition of organolithium reagents to η^6-$Cr(CO)_3$-arene imine complex **28** and its application in the total synthesis of (-)-acetoxylbutipofuran was published by Kündig (Scheme 9).[19] The observed enantioselectivity was rationalized by addition of the organolithium reagent at the *ortho* position rather than the *ortho'* position. This regioselectivity was induced by the steric congestion between the Ph group of the chiral ligand and the $Cr(CO)_3$ group in transition state II. The resulting cyclohexadienyl intermediate **29** underwent sequential acylation, alkylation and imine hydrolysis to afford **30** in 42% yield and 76% ee. Recrystallization of **30** increased the enantiopurity to > 99% ee. High enantiopurity **30** was converted to carbonate **31** *via* Luche reduction followed by selective protection of primary and secondary hydroxyl groups. Finally, (-)-acetoxylbutipofuran was synthesized from **31** in 8 more steps.

[19] Kündig, E. P.; Cannas, R.; Laxmisha, M.; Liu, R.; Tchertchian, S. *J. Am. Chem. Soc*. **2003**, *125*, 5642-5643.

Scheme 9. Total synthesis of (-)-Acetoxytubipofuran *via* Chromium-mediated Asymmetric Dearomatization



Molybdenum Complexes

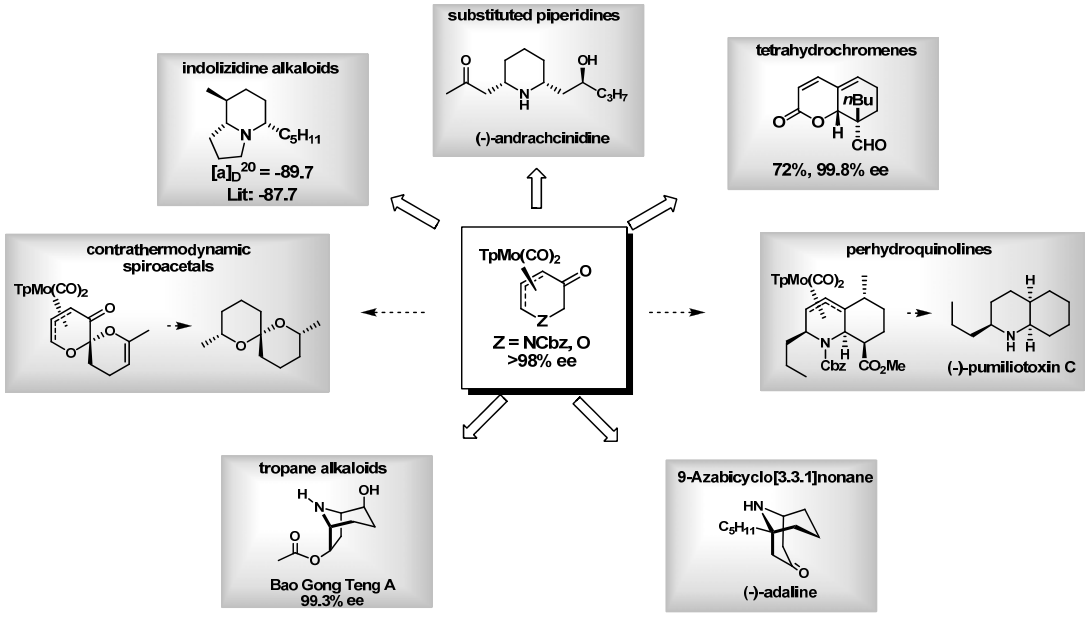
High enantiopurity η^3-pyanyl and η^3-pyridinyl molybdenum complexes[20] are easily prepared, and have been demonstrated as versatile enantiomeric scaffolds in the synthesis of complex organic molecules. Since 1999, a number of structurally diverse molecules (Scheme 10) have been synthesized by Liebeskind's group utilizing molybdenum-mediated reactions.[21]

---

[20] Coombs, T. C.; Lee IV, M. D.; Wong, H.; Armstrong, M.; Cheng, B.; Chen, W.; Moretto, A. F.; Liebeskind, L. S. *J. Org. Chem.* **2008**, *73*, 882-888.

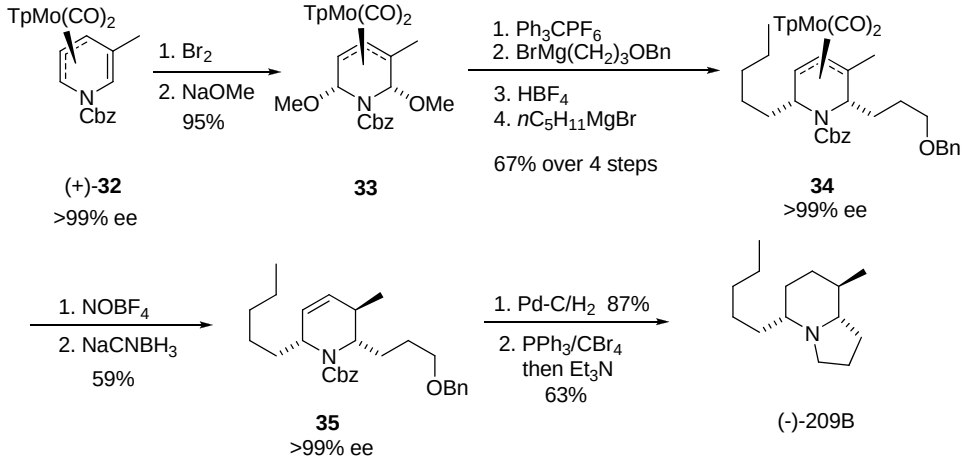
[21] (a) Yin, J.; Liebeskind, L. S. *J. Am. Chem. Soc.* **1999**, *121*, 5811-5812. (b) Yin, J.; Llorente, I.; Villanueva, L. A.; Liebeskind, L. S. *J. Am. Chem.Soc.* **2000**, *122*, 10458-10459. (c) Malinakova, H. C.; Liebeskind, L. S. *Org. Lett.* **2000**, *2*, 3909-3911. (d) Malinakova, H. C.; Liebeskind, L. S. *Org. Lett.* **2000**, *2*, 4083-4086. (e) Shu, C.; Alcudia, A.; Yin, J.; Liebeskind, L. S. *J. Am. Chem. Soc.* **2001**, *123*, 12477-12487. (f) Arrayás, R. G.; Liebeskind, L. S. *J. Am. Chem. Soc.* **2001**, *123*, 6185-6186. (g) Shu, C.; Liebeskind, L. S. *J. Am. Chem. Soc.* **2003**, *125*, 2878-2879. (h) Arrayás, R. G.; Liebeskind, L. S. *J. Am. Chem. Soc.* **2003**, *125*, 9026-9027. (i) Zhang, Y.; Liebeskind, L. S. *J. Am. Chem. Soc.* **2005**, *127*, 11258-11259. (j) Zhang, Y.; Liebeskind, L. S. *J. Am. Chem. Soc.* **2006**, *128*, 465-472. (k) Arrayás, R. G.; Yin, J.; Liebeskind, L. S. *J. Am. Chem. Soc.* **2007**, *129*, 1816-1825. (l) Garnier, E. C.; Liebeskind, L. S. *J. Am. Chem. Soc.* **2008**, *130*, 7449-7458.

Scheme 10. Molybdenum-mediated Organic Synthesis



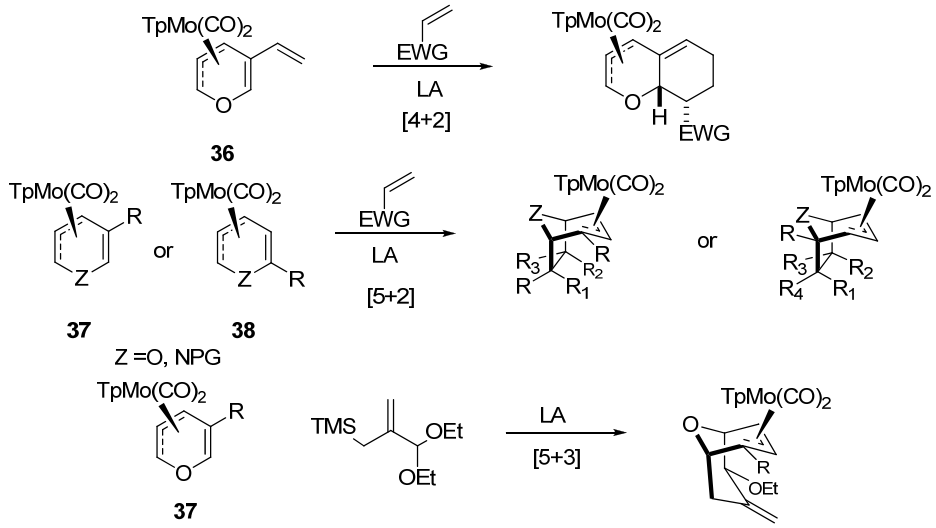
In 2001, a molybdenum-mediated enantiocontrolled route to 2,3,6-*cis*- and 2,6-*cis*-3-*trans*-trisubstituted was reported.[21e] This novel methodology was employed in the total synthesis of (-)-indolizidine 209B (Scheme 11). Molybdenum complex (+)-**32** (> 99% ee) was first converted to dimethoxy complex **33** in 95% yield by bromination followed by addition of NaOMe. Then highly selective methoxide abstraction followed by nucleophilc addition of different carbon nucleophiles afforded **34** in 67% yield and 99% ee. Regio- and stereoselective demetalation of 2,3,6-trisubstituted molybdenum complex **34** provided **35** in 99% ee which was converted to (-)-indolizidine 209B over 2 steps.

Scheme 11. Enantiocontrolled Total Synthesis of (-)-Indolizidine 209B Using (η^3-dihydropyridinyl)molybdenum Complexes as Chiral Scaffolds



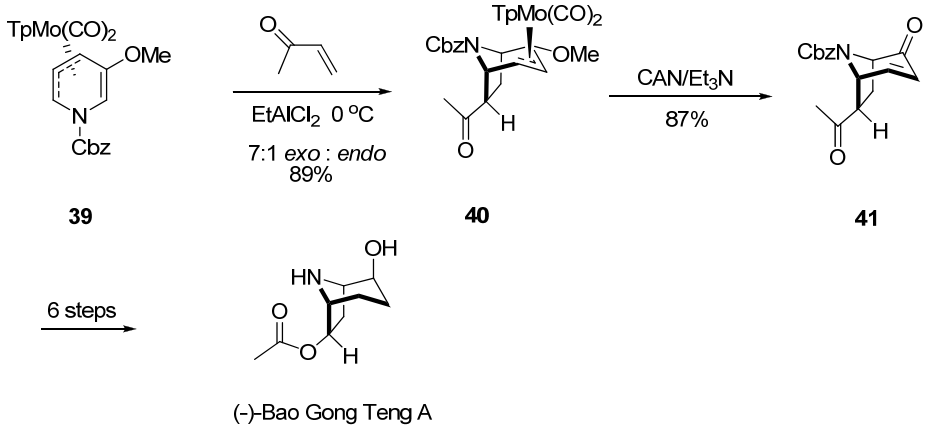
Unsaturated molybdenum complexes such as **36**, **37** and **38** can be utilized as chiral scaffolds for the rapid synthesis of various bridged and fused hetereocyclic ring systems *via* molybdenum-mediated [4+2],[21f,k] [5+2][21a,c,d,i] and [5+3][21h] cycloadditions (Scheme 12).

Scheme 12. Molybdenum-mediated Cycloaddition Reactions



Utilizing the molybdenum-mediated **[**5+2] cycloaddition, (-)-Bao Gong Teng A, a Chinese herb medicine, was synthesized in 2006 (Scheme 13).[21j] Unsaturated molybdenum complex **39** underwent a regio- and stereocontrolled **[**5+2] cycloaddition with methyl vinyl ketone gave molybdenum complex **40** in 89% yield (*exo*:*endo* 7:1). Oxidative decomplexation of **40** with CAN afforded the requisite bicyclic diketone **41** in 87% yield. Finally, **41** was converted to (-)-Bao Gong Teng A in 45% yield and > 99% ee over 6 steps.

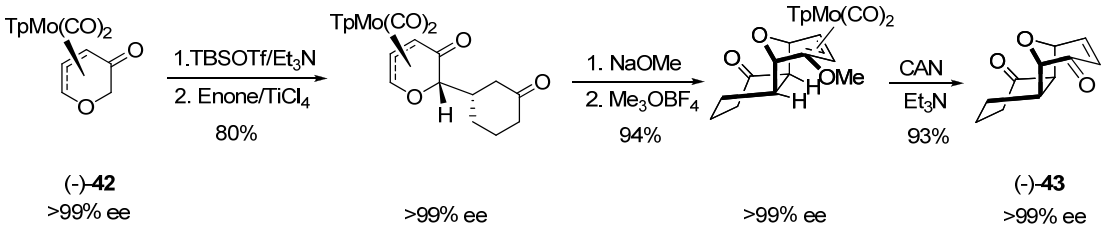
Scheme 13. Total Synthesis of (-)-Bao Gong Teng A by a Molybdenum-mediated [5+2] Cycloaddition



In 2005 an unprecedented molybdenum-mediated '1,5-Michael-like' reaction was reported,[21i] in which neutral $TpMo(CO)_2(\eta^3$-pyranyl) and $TpMo(CO)_2(\eta^3$-pyridinyl) complexes underwent direct nucleophilic addition of an internal enolate to the terminus of the allylmolybdenum moiety, and formed a new carbon-carbon bond. Employing this methodology, tricyclodione (-)-**43** (Scheme 14) was prepared in > 99% ee from

5-oxopyanyl molybdenum complex (-)-**42** (> 99% ee) through sequential Mukaiyama-Michael, '1,5-Michael-like' reaction and decomplexation reactions.

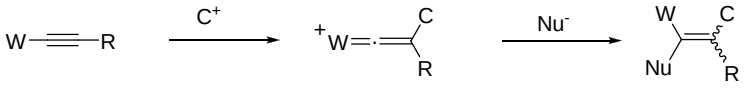
Scheme 14. Enantiocontrolled Synthesis of Tricyclodiones *via* a Molybdenum-mediated '1,5-Michael-like' Reaction



Tungsten Complexes

The synthesis of complex organic molecules using organotungsten complexes has been extensively studied by Liu's group.[1f] η^1-Alkynyl, η^3-allyl and η^1-propargyl tungsten complexes are among those most popular organotungsten species. η^1-Alkynyl tungsten complexes are particularly useful since they can react with electrophiles at β-carbon and form a metal-η^1-vinylidenium intermediate which undergoes nucleophilic addition regiospecifically at the α-carbon (Scheme 15).

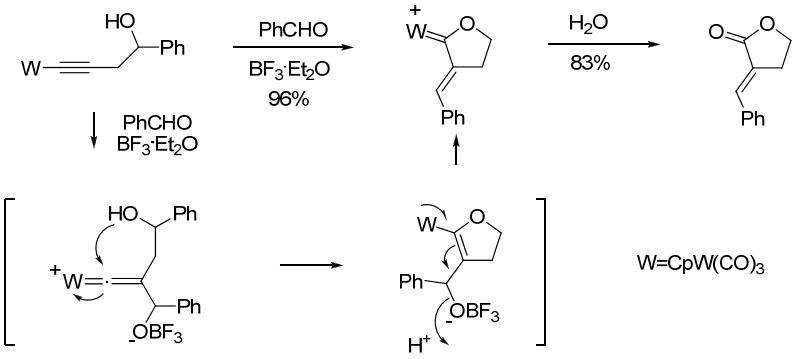
Scheme 15. Reactivity of η^1-Alkynyl Tungsten Complexes



W=CpW(CO)3

Taking advantage of this reactivity, Liu reported the synthesis of tungsten-furanyl diene[22] by treatment of alkynyltungsten complexes with RCH_2CHO and $BF_3{\cdot}Et_2O$. The mechanism of this reaction is shown in Scheme 16.

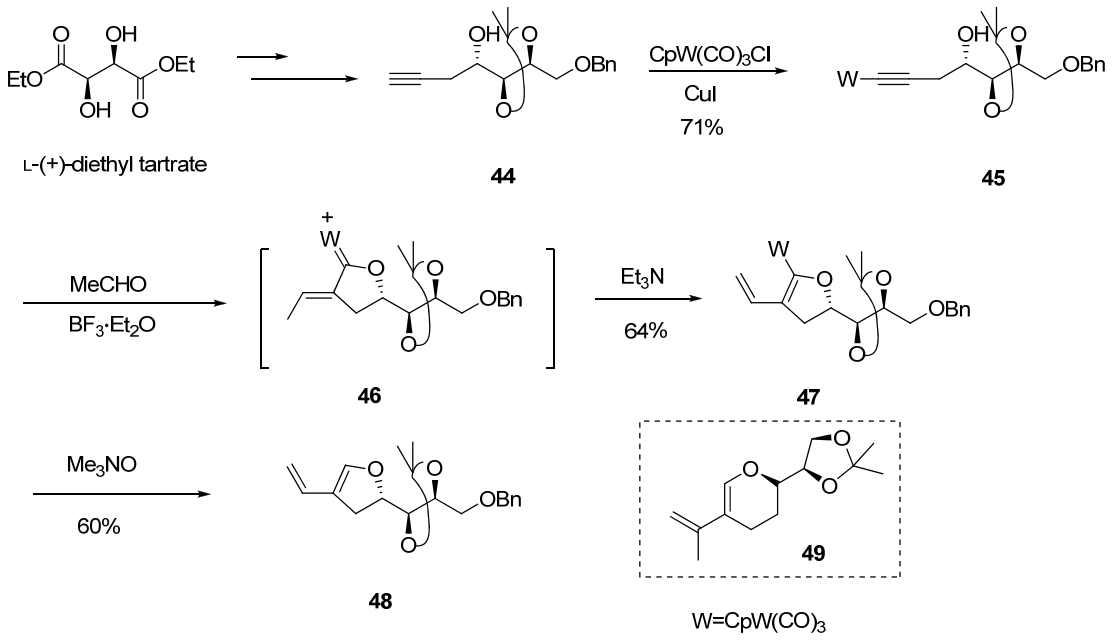
Scheme 16. Mechanism of the Synthesis of Tungsten-furanyl Diene



In 2003, Liu reported the synthesis of chiral furanyl and pyranyl diene[23] through this methodology (Scheme 17). Alkynol **44** was first prepared from L-(+)-diethyl tartrate. Metalation of **44** with $CpW(CO)_3Cl$ afforded tungsten-alkynol complex **45** in 71% yield. Reaction of **45** with acetaldehyde and $BF_3{\cdot}Et_2O$ afforded salt **46** which was directly treated with Et_3N to afford tungsten diene **47** in 64% yield. Finally, hydrodemetalation of **47** with Me_3NO afford chiral furanyl diene **48** in 60% yield. Chiral pyranyl diene **49** was also successfully prepared through a similar approach.

[22] Liang, K.; Li, W.; Lee, G.; Peng, S.; Liu, R. *J. Am.Chem. Soc.* **1997**, *119*, 4404-4412.
[23] Huang, H.; Liu, R. *J. Org. Chem.* **2003**, *68*, 805-810.

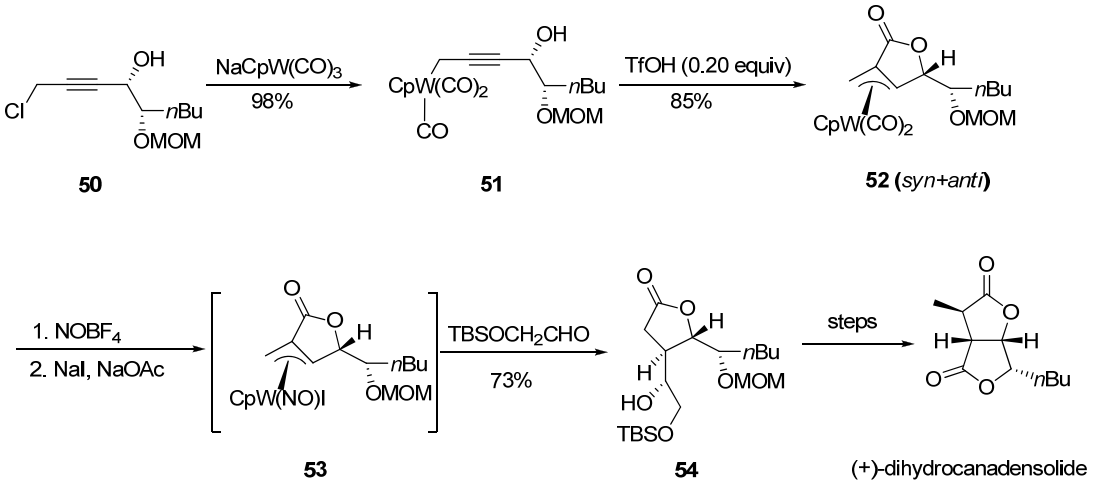
Scheme 17. Tungsten-mediated Synthesis of Chiral Furanyl Diene



In 1999, Liu and co-workers reported the total synthesis of (+)-dihydrocanadensolide[24] through a tungsten-π-allyl-complex as shown in Scheme 18. Metalation of chiral propargyl substrate **50** with $NaCpW(CO)_3$ gave η^1-propargyl tungsten complex **51** in 98% yield. Treatment of **51** with catalytic amount of triflic acid induced an intramolecular alkoxycarbonylation reaction, and afforded π-allyl tungsten complex **52** in 85% yield as a mixture of *syn* and *anti* isomers. Ligand exchange with $NOBF_4$ and NaI led to the formation of **53** that reacted *in situ* with $TBSOCH_2CHO$ to furnish compound **54** in 73% yield. Compound **54** was converted to (+)-dihydrocanadensolide in 7 steps.

[24] Chen, M.; Narkunan, K.; Liu, R. *J. Org. Chem*. **1999**, *64*, 8311-8318.

Scheme 18. Total Synthesis of (+)-Dihydrocanadensolide through a Tungsten-π-allyl-complexes



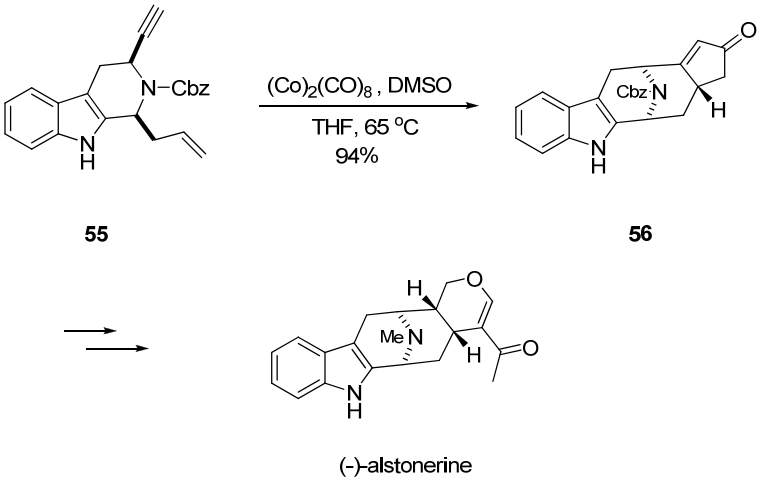
Cobalt Complexes

Organocobalt complexes are widely utilized to mediate different type of organic reactions, including Diels-Alder reaction, cobaloxime π-cation cyclizations, Pauson-Khand reaction, Nicholas reaction and cobalt mediated oxidation and reduction reaction.[25] Since its first report in 1970's,[26] the Pauson-Khand reaction became the most heavily studied organocobalt mediated reaction.[27] The required alkyne cobalt intermediates are easily prepared by reacting alkynes with stoichiometric dicobalt octacarbonyl (catalytic Pauson-Khand reactions were also reported under high pressure of carbon monoxide). Martin reported the enantioselective total synthesis of (-)-alstonerine[28] which featured the first application of Pauson-Khand reaction in the synthesis of azabridged bicyclic

[25] For a comprehensive review, see: Welker, M. E. *Curr. Org. Chem.* **2001**, *5*, 785-807.
[26] Khand, I. U.; Knox, G. R.; Pauson, P. L.; Watts, W. E.; Foreman, M. I. *J. Chem. Soc., Perkin Trans. 1* **1973**, 977-981.
[27] For reviews, see: (a) Gibson, S. E.; Mainolfi, N. *Angew. Chem., Int. Ed. Engl.* **2005**, *44*, 3022-3037. (b) Blanco-Urgoiti, J.; Anorbe, L.; Perez-Serrano, L.; Dominguez, G.; Perez-Castells, J. *Chem. Soc. Rev*. **2004**, *33*, 32-42.
[28] Miller, K. A.; Martin, S. F. *Org. Lett.* **2007**, *9*, 1113-1116.

skeleton (Scheme 19). In this total synthesis, Pauson-Khand reaction of enyne **55** with stoichiometric dicobalt octacarbonyl gave cyclopentenone **56** in 94% yield as a single diastereomer, whereas various catalytic conditions only led to the recovery of starting materials.

Scheme 19. Total Synthesis of (-)-Alstonerine

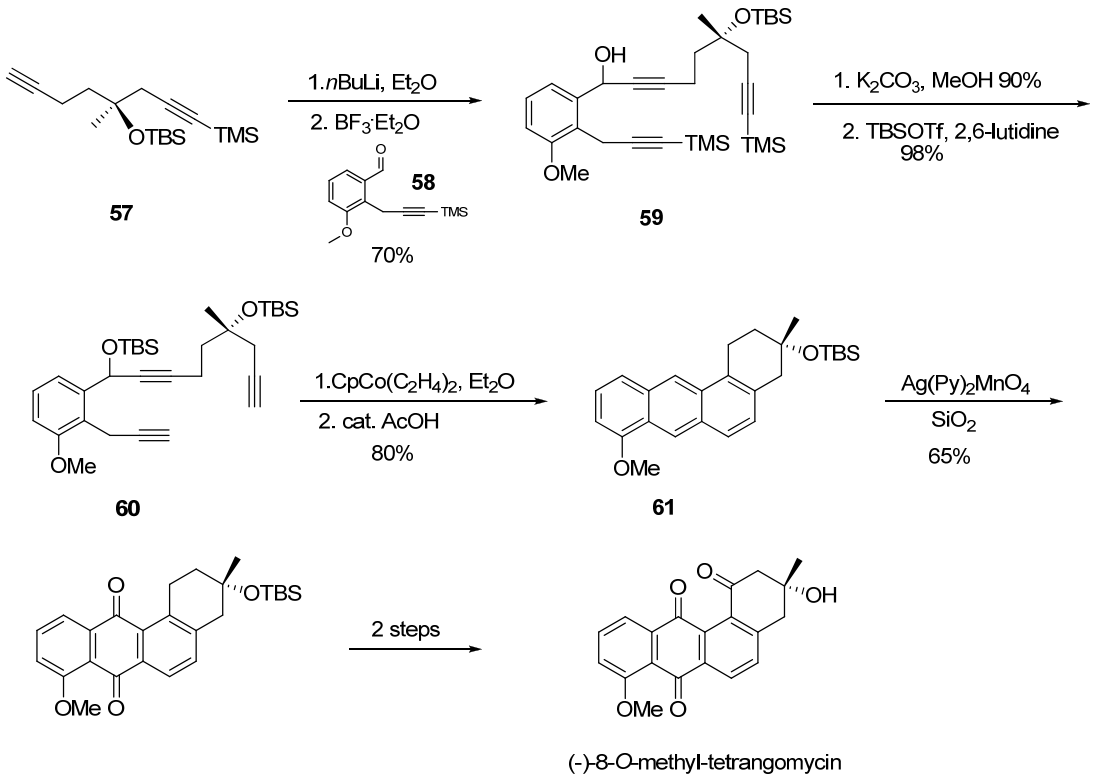


A stereoselective total synthesis of antibiotic (-)-8-*O*-methyltetrangomycin was reported by Groth (Scheme 20),[29] that employed a cobalt mediated [2+2+2] cycloaddition[30] to access the core structure. Addition of lithiated diyne **57** to substituted benzaldehyde **58** afforded compound **59** which was converted to triyne **60** after deprotection of the trimethylsilyl group and protection of the free hydroxyl group. Cyclization of **60** by cobalt mediated [2+2+2] cycloaddition afforded tetrahydrobenz[*a*]anthracene **61** in 80% yield when using equimolar "jonas" catalyst $CpCo(C_2H_4)_2$. The synthesis of

[29] Kesenheimer, C.; Groth, U. *Org. Lett.* **2006**, *8*, 2507-2510.
[30] For reviews, see: (a) Gandon, V.; Aubert, C.; Malacria, M. *Chem. Comm.* **2006**, 2209-2217. (b) Varela, J. A.; Saá, C. *Chem. Rev.* **2003**, *103*, 3787-3801.

(-)-8-*O*-methyltetrangomycin was completed in 38% yield over three steps from **61**.

Scheme 20. Total Synthesis of (-)-8-*O*-Methyltetrangomycin *via* a Cobalt Mediated [2+2+2] Cycloaddition

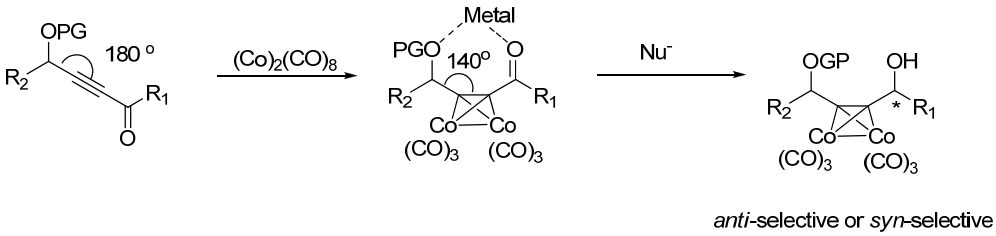


In 2008, Hiyashi's group reported a novel highly diastereoselective 1,4-asymmetric induction[31] using a cobalt alkyne complex (Scheme 21). This is the first example of using a cobalt alkyne complex for a stereoselective reaction *via* 1,4-chelation. As shown in Scheme 21, the angle of the alkyne triple bond is 180 °, whereas that of the alkyne cobalt complex is about 140 °. Complexation forces the stereogenic and prestereogenic centers closer to each other, which makes the metal chelation possible, thus generating

[31] Hayashi, Y.; Yamaguchi, H.; Toyoshima, M.; Nasu, S.; Ochiai, K.; Shoji, M. *Organometallics* **2008**, *27*, 163-165.

highly stereoselective 1,4-asymmetric induction.

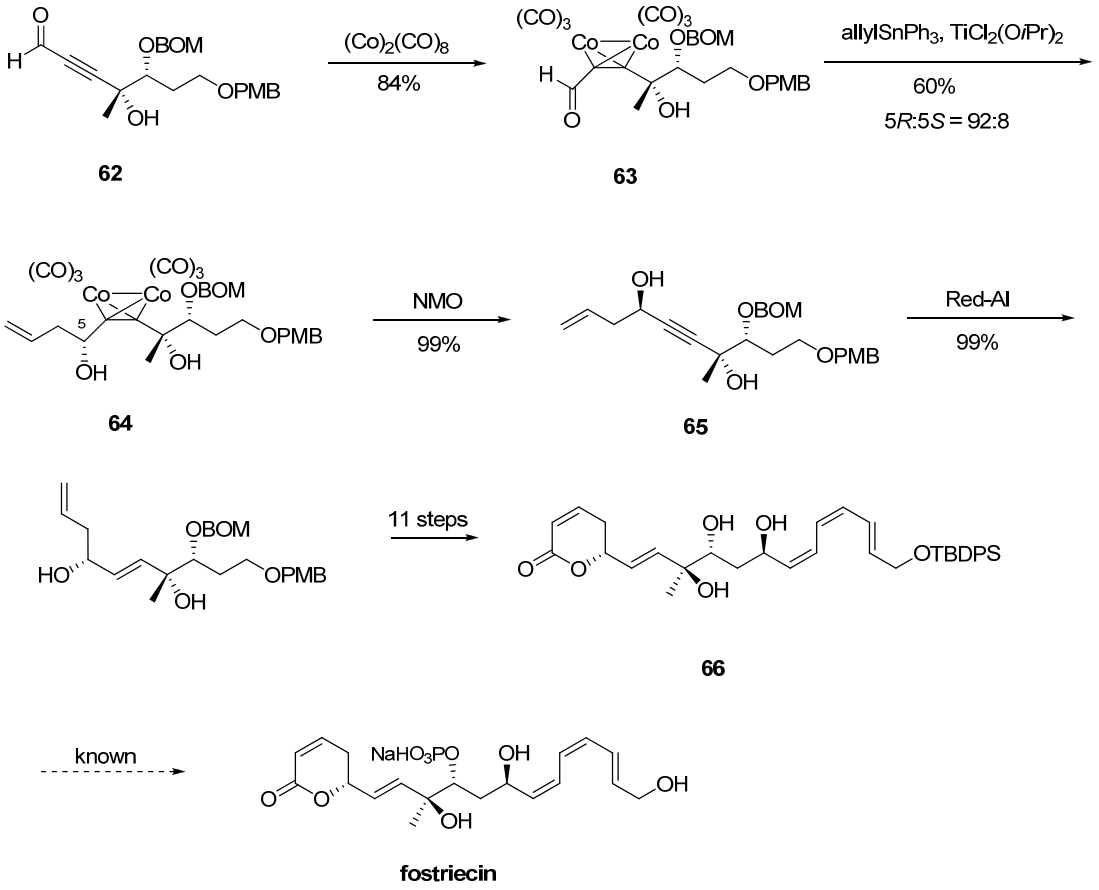
Scheme 21. 1,4-Asymmetric Induction Using a Cobalt Alkyne Complex



Later, this methodology was utilized in the formal total synthesis of fostriencin[32] (Scheme 22). Upon treatment of dicobalt octacarbonyl, compound **62** was converted to isolable cobalt alkyne complex **63** in 84% yield. The crucial 1,4-asymmetric induction was achieved by using $TiCl_2(O\textit{i}Pr)_2$ mediated allylation. Removal of cobalt with NMO afforded compound **65** in excellent yield. Compound **65** was further transformed to dephosphofostriecin **66** in 11 steps which is a known key intermediate[33] to access fostriencin.

[32] Hayashi, Y.; Yamaguchi, H.; Toyashima, M.; Okado, K.; Toyo, T.; Shoji, M. *Org. Lett.* **2008**, *10*, 1405-1408.
[33] Miyashita, K.; Ikejiri, M.; Kawasaki, H.; Maemura, S.; Imanishi, T. *J. Am. Chem. Soc.* **2003**, *123*, 8238-8243.

Scheme 22. Formal Total Synthesis of Fostriencin *via* 1,4-Asymmetric Induction Using a Cobalt Alkyne Complex



Iron complexes

η^4-Diene iron complexes are widely used in organic synthesis due to their convenient preparation, decomplexation, novel reactivity, and compatibility with a wide range of functional groups.[34] Since those complexes are stable under various reaction conditions, η^4-diene iron complexes can be used as 1,3-diene protecting group and stereochemical directing group. Neutral 1,3-diene iron complexes can be converted to cationic dienyl

[34] For a recent review, see: Donaldson, W. A. *Curr. Org. Chem*. **2000**, *4*, 837-868.

complexes which are reactive to a broad range of nucleophiles, and more importantly, the presence of iron provides unique stereo- and regioselectivity to these diene complexes.[35]

In 2008, a formal total synthesis of (±)-maritidine[36] was accomplished by Stephenson and co-workers using cyclohexadienyl iron complex **67** (Scheme 23). Addition of aryllithium reagent **68** to complex **67** afforded 1-arylcyclohexadienyliron complex **69** in 57% yield. Methoxide abstraction with Ph_3CBF_4 provided isolable salt **70** in 70% yield. One-pot malononitrile addition/*in situ* desilylation/dealkoxylation/decarboxylation combined with deprotection of the benzylic alcohol furnished organonitrile **71** in 73% yield. After reduction of the nitrile (67%), cyclization under standard conditions gave tricyclic complex **72** in 47% yield. Finally, protection of the secondary amine followed by decomplexation afforded spiralcyclohexenone **73** which was a known intermediate to (±)-Maritidine.

Knölker and co-workers developed an iron-mediated oxidative cyclization using air as oxidant. This methodology was applied to the total synthesis of carbazole alkaloids mukonine[37] in 2003 (Scheme 24). Electrophilic substitution of **74** with dienyl iron complex salt **75** at room temperature afforded complex **76** in 61% yield. Stirring of **76** in toluene with TFA led to a smooth cyclodehydrogenation and afforded diene iron complex **77** in 50% yield. Oxidative decomplexation of **77** with ferricenium hexafluorophosphate in the presence of sodium carbonate gave mukonine in 50% yield.

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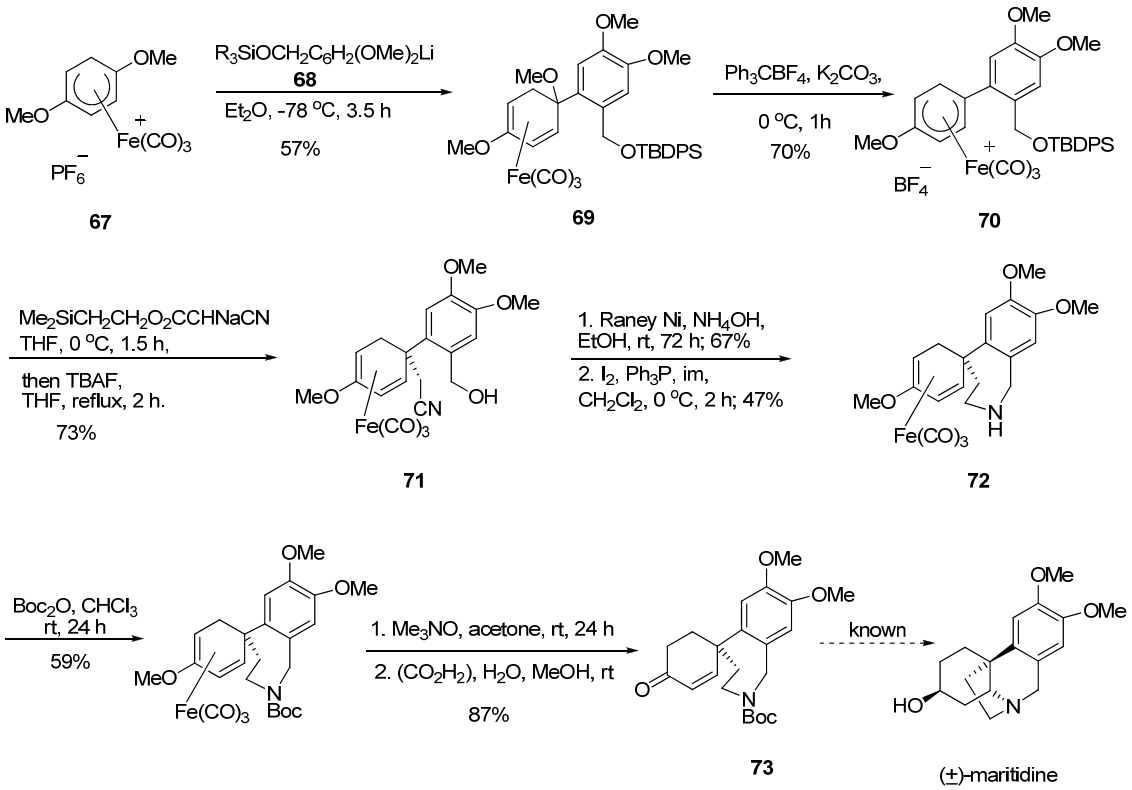
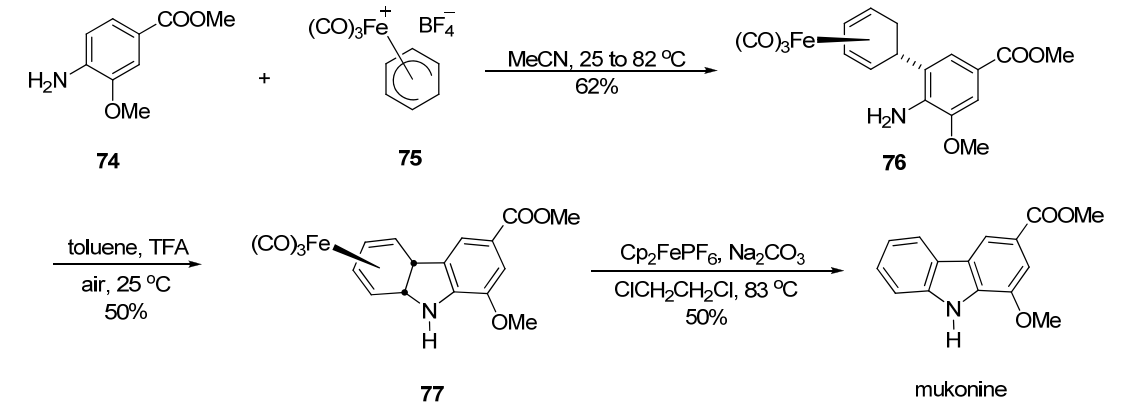
[35] For reviews, see: (a) Pearson, A. J. *Science* **1984**, 223, 895-901. (b) Pearson, A. J. In *Comprehensive Organic Synthesis*; Trost, B. M; Fleming, I., Eds.; Pergamon: Oxford, 1991; Vol. 4, p 665-689.
[36] Roe, S.; Stephenson, G. R. *Org. Lett.* **2008**, *10*, 189-192.
[37] Knölker, H-J.; Wolpert, M. *Tetrahedron* **2003**, *59*, 5317-5322.

Scheme 23. Iron-mediated Total Synthesis of (±)-Maritidine



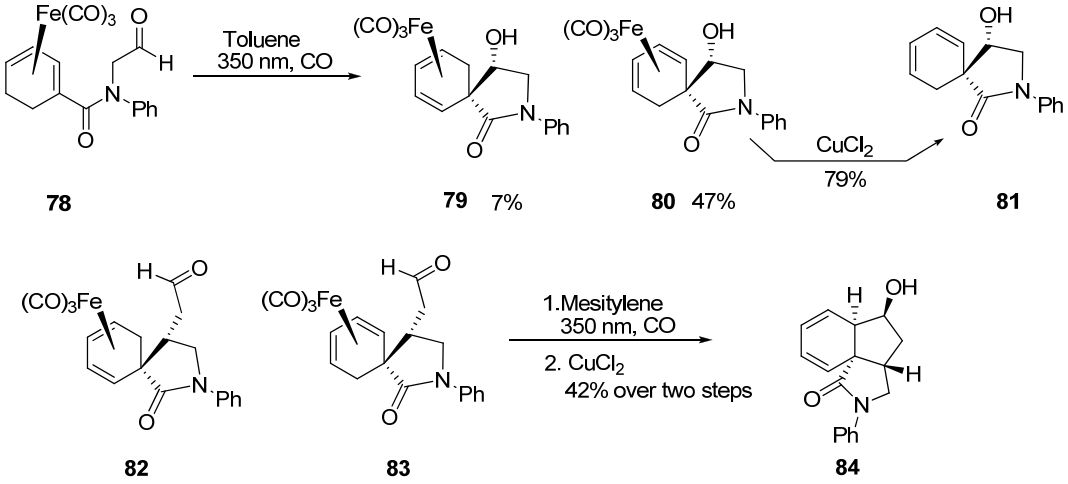
Scheme 24. Iron-mediated Total Synthesis of Mukonine



Pearson's group developed an intramolecular iron tricarbonyl promoted [6+2] ene type of spirocyclization reaction in which a cyclohexadieneiron tricarbonyl moiety couples with

a pendant olefin to afford two diastereomeric spirocyclic iron complexes.[38] Recently, they successfully expanded the scope of this methodology to an intramolecular iron-tricarbonyl promoted aldehyde-diene coupling reaction (Scheme 25).[39] Under photothermal conditions, complex **78** underwent intramolecular cyclocoupling to afford **79** and **80** in 54% yield and around 1 : 7 ratio. Iron complex **80** was converted to diene **81** by oxidative decomplexation with $CuCl_2$ in 79% yield. More complex substrates **82** and **83** also participated in this reaction, and afforded tricyclic diene **84** in 42% yield over 2 steps.

Scheme 25. Intramolecular Iron-tricarbonyl Promoted Aldehyde-diene Coupling Reaction

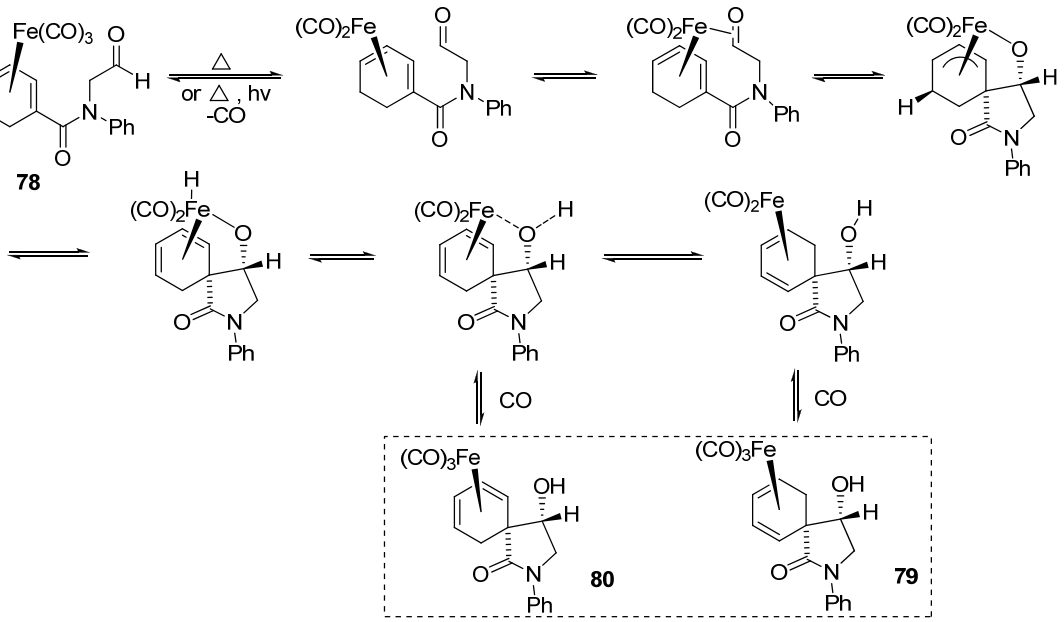


Possible mechanism of this intramolecular iron mediated carbonyl-ene spirocyclization is shown in Scheme 26. This proposed mechanism is similar to the previously reported all

[38] (a) Pearson, A. J.; Zettler, M. W. *J. Am. Chem. Soc.* **1989**, *111*, 3908-3918. (b) Pearson, A. J.; Wang, X. *J. Am. Chem. Soc.* **2003**, *125*, 13326-13327. (c) Pearson, A. J.; Wang, X.; Dorange, I. B. *Org. Lett.* **2004**, *6*, 2535-2538. (d) Pearson, A. J.; Sun, H.; Wang, X. *J. Org. Chem.* **2007**, *72*, 2547-2557.
[39] Pearson, A. J.; Sun, H. *J. Org. Chem*. **2007**, *72*, 7693-7700.

carbon spirocyclization reaction.[38a] The preference for the formation of **80** is probably due to coordination of the iron atom with the newly formed hydroxyl group, thus slowing down the diene migration to form **79**.

Scheme 26. Proposed Mechanism for Intramolecular Iron-tricarbonyl Promoted Aldehyde-diene Coupling Reaction



Conclusion

Transition metal complexes imparted novel reactivity and selectivity to their attached organic fragments, thus providing unique opportunities to construct various organic molecules. Along with the continuing discovery of novel reactivity and development of convenient preparation of enantiomerically pure organometallic complexes, the application of stoichiometric transition metal complexes in the total synthesis of natural products will attract more attention in the synthetic community.

Chapter 2

Synthesis of 6,8-Dioxabicyclo[3.2.1]oct-3-en-2-one through a Molybdenum-mediated Intramolecular ‘1,5-Michael-like’ Reaction

Introduction

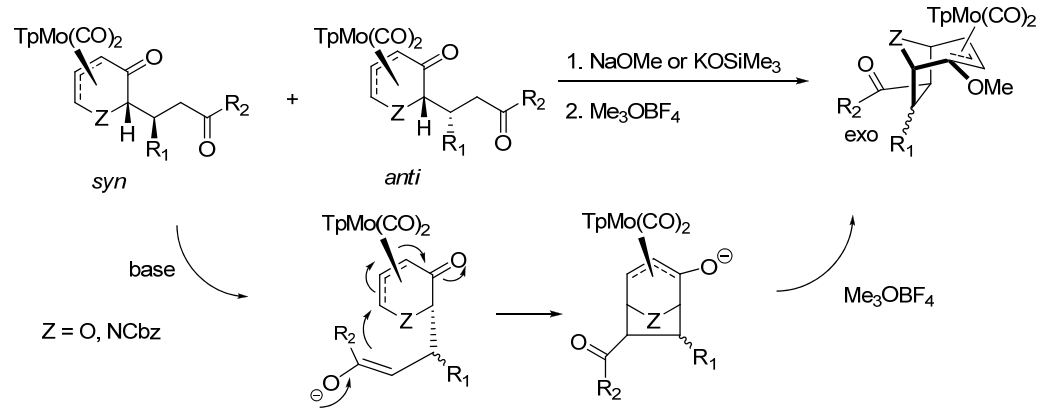
As versatile organometallic enantiomeric scaffolds, high enantiopurity TpMo(CO)$_2$(η^3-pyranyl) and TpMo(CO)$_2$(η^3-pyridinyl) complexes have been utilized in the asymmetric construction of structurally diverse heterocyclic systems. Different strategies including molybdenum mediated sequential functionalization [40] and cycloaddition reactions[41] have been applied in the elaboration of the enantiomeric scaffolds. Although neutral η^3-allylmolybdenum complexes are normally considered unreactive toward direct nucleophilic functionalization on the π-carbon, recently, an unprecedented '1,5-Michael-like' reaction[42] (Scheme 27) was reported in which neutral TpMo(CO)$_2$(η^3-pyranyl) and TpMo(CO)$_2$(η^3-pyridinyl) complexes underwent direct nucleophilic addition of an internal enolate to the terminus of an allylmolybdenum moiety, and formed a new carbon-carbon bond.

[40] (a) Yin, J.; Llorente, I.; Cillanueva, L. A.; Liebeskind, L. S. *J. Am. Chem. Soc*. **2000**, *122*, 10458-10459. (b) Shu, C.; Alcudia, A.; Yin, J.; Liebeskind, L. S. *J. Am. Chem. Soc*. **2001**, *123*, 12477-12487. (c) Shu, C.; Liebeskind, L. S. *J. Am. Chem. Soc*. **2003**, *125*, 2878-2879.

[41] (a) Yin, J.; Liebeskind, L. S. *J. Am. Chem. Soc.* **1999**, *121*, 5811–5812. (b) Malinakova, H.; Liebeskind, L. S. *Org. Lett.*. **2000**, *2*, 3909-3911. (c) Malinakova, H. C.; Liebeskind, L. S. *Org. Lett.* **2000**, *2*, 4083–4086. (d) Arrayás, R. G.; Liebeskind, L. S. *J. Am. Chem. Soc*. **2003**, *125*, 9026. (e) Zhang, Y.; Liebeskind, L. S. *J. Am. Chem. Soc.* **2006**, *128*, 465-472. (f) Arrayás, R. G.; Yin, J.; Liebeskind, L. S. *J. Am. Chem. Soc.* **2007**, *129*, 1816–1825. (g) Garnier, E. C.; Liebeskind, L. S. *J. Am. Chem. Soc.* **2008**, *130*, 7449-7458.

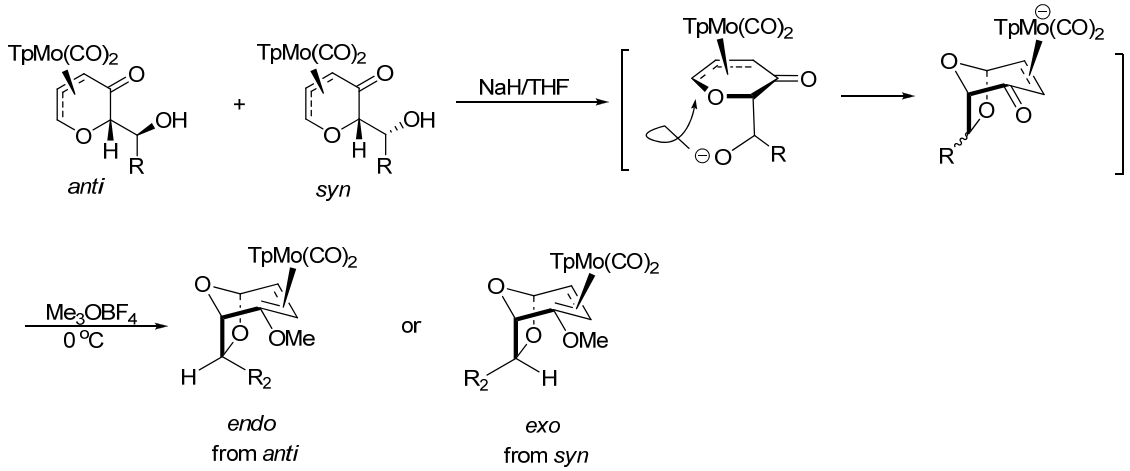
[42] Zhang, Y.; Liebeskind, L. S. *J. Am. Chem. Soc.* **2005**, *127*, 11258-11259.

Scheme 27. Intramolecular '1,5-Michael-like'Reaction of Enolate



Intrigued by this unusual reactivity of neutral η^3-allylmolybdenum complexes, we decided to examine the scope of this type of reaction. Herein we report that TpMo(CO)$_2$(η^3-pyranyl) complexes bearing an internal alkoxide can participate in intramolecular '1,5-Michael-like' reactions, and a new carbon-oxygen bond is formed regio- and stereospecifically (Scheme 28). Moreover, through a one-pot '1,5-Michael-decomplexation' sequence, a variety of complex organic molecules featuring the 6,8-dioxabicyclo[3.2.1]octane framework can be rapidly accessed with complete stereocontrol. The synthetic potential of this methodology was demonstrated by a highly enantiocontrolled total synthesis of (+)-(1*R*,2*S*,5*S*,7*R*)-2-hydroxy-*exo*-brevicomin.

Scheme 28. Intramolecular '1,5-Michael-like' Reaction of Alkoxide

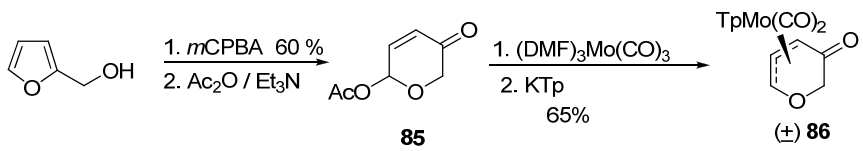


Results and Discussion

Synthesis of Racemic and Chiral, Non-racemic 5-Oxapyranyl Scaffold 86

The racemic 5-oxopyranyl scaffold **86** was prepared from furfuryl alcohol through sequential Achmatowicz rearrangement,[43] acetylation of the corresponding alcohol and complexation with $(DMF)_3Mo(CO)_3$ followed by ligand exchange with potassium hydridotris(1-pyrazolyl)borate[44](KTp) (Scheme 29).[45]

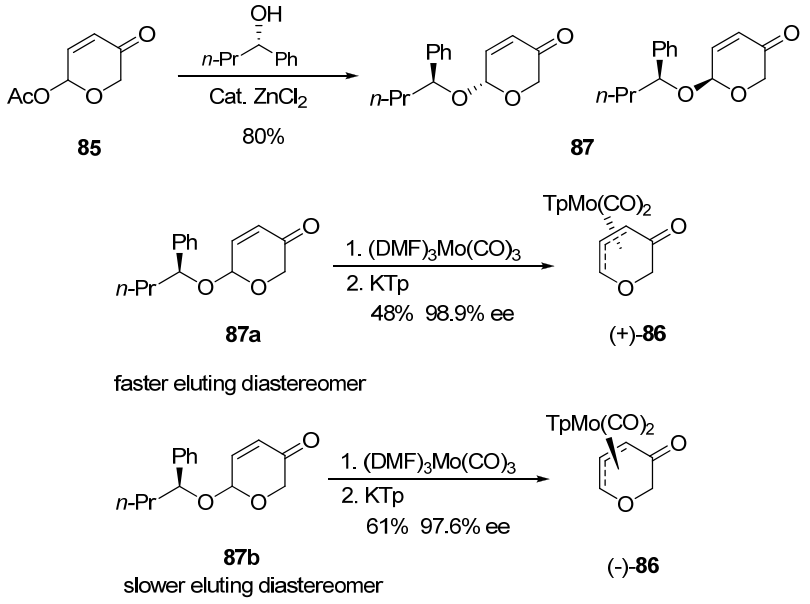
Scheme 29. Synthesis of Racemic 5-Oxopyranyl Scaffold 86



[43] Achmatowicz, O., Jr.; Bukowski, P.; Szechner, B.; Zwierzchowska, Z.; Zamojski, A. *Tetrahedron* **1971**, *27*, 1973-1996.
[44] Trofimenko, S. *J. Am. Chem. Soc.* **1967**, *89*, 3170-3177.
[45] Coombs, T. C.; Lee, M. D., IV; Wong, H.; Armstrong, M. A.; Cheng, B.; Chen, W.; Moretto, A. F.; Liebeskind, L. S. *J. Org. Chem.* **2008**, *73*, 882-888.

Both antipodes of chiral, non-racemic scaffold **86** can be synthesized as depicted in Scheme 30.[45] Racemic allylic acetate **85** was first converted to substituted pyranone **87** by $ZnCl_2$-mediated diastereomer formation with commercially available (*S*)-1-phenyl butanol. The two diastereomers of **87** can be resolved by chromatography. Then **87a** (faster eluting diastereomer) and **87b**[46] (slower eluting diastereomer) underwent oxidative addition to $(DMF)_3Mo(CO)_3$; Subsequent treatment with KTp gave (+)-**86** (48%, 98.9% ee) and (-)-**86** (61%, 97.6% ee) respectively. After recrystallization, the enantiopurity of both (+)-**86** and (-)-**86** can be increased to > 99% ee.

Scheme 30. Synthesis of Chiral, Non-racemic 5-Oxopyranyl Scaffold 86



In an earlier report, (*R*)-pantolactone derived pyranones underwent oxidative addition to

[46] Because **87A** and **87B** are liquids, the absolute configurations haven't been determined yet.

$(DMF)_3Mo(CO)_3$ predominantly with inversion of configuration.[47] Compared to previous methods with pantolactone, this improved approach probably minimized the formation of undesired enantiomer from a coordination-induced retention pathway[48](Figure 1), thus providing (-)-**86** and (+)-**86** with higher enantiopurity after complexation.[45]

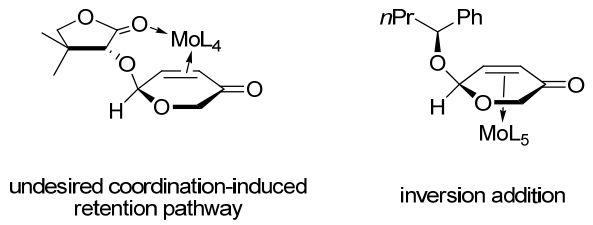


Figure 1. Two Possible Mechanisms for Enantiocontrolled Complexation

Mukaiyama-aldol Reaction and Aldol Reaction of 5-Oxopyranyl Scaffold 86 and 2-Methyl-5-oxopyranyl Scaffold 88

The synthetic studies of the intramolecular '1,5-Michael-like' reaction started with transformation of (±)-5-oxopyranyl complex **86** and **88**[49] (Figure 2) to the corresponding alcohols **89** by Mukaiyama-aldol or traditional aldol reactions.

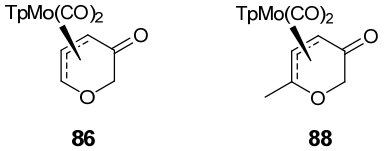
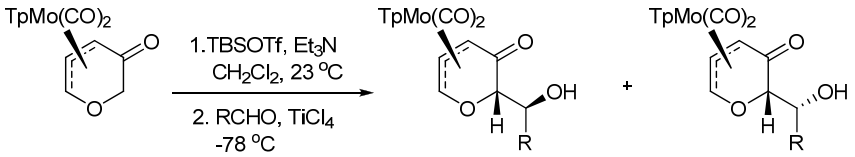


Figure 2. (±) 5-Oxopyranyl Complex 86 and 88

[47] Yin, J.; Liebeskind, L. S. *J. Am. Chem. Soc.* **1999**, *121*, 5811-5812.
[48] Ward, Y. D.; Villanueva, L. A.; Allred, G. D.; Liebeskind, L. S. *J. Am. Chem. Soc.* **1996**, *118*, 897-898.
[49] Synthesis of complex **88** will be discussed later in this chapter.

As shown in Table 1, Mukaiyama-aldol reaction of (±)-5-oxopyranyl complex **86** with different aldehyde[50] gave good to excellent combined yields of the corresponding *anti* and *syn* alcohols. The relative configurations of these alcohols were determined by comparing the vicinal coupling constant between the hydrogen adjacent to the hydroxyl group and the hydrogen on the pyran ring,[51] and further confirmed by X-ray diffraction analysis.[52]

Table 1. Mukaiyama-aldol Reaction of Oxopyranyl Scaffold 86



86 *anti*-**89** *syn*-**89**

Entry	Ketone	Aldehyde	*anti*:*syn*	% Yield	%ee
1	(-)-**86**	acetaldehyde	2:1	85, (-)-**89a**	98.7[a]
2	(±)-**86**	propaldehyde	1:1	76, **89b**	
3	(±)-**86**	crotonaldehyde	2:1	41, **89c**	
4	(±)-**86**	PhCHO	9:1	90, **89d**	
5	(±)-**86**	3-NO_2PhCHO	4:1	88, **89e**	

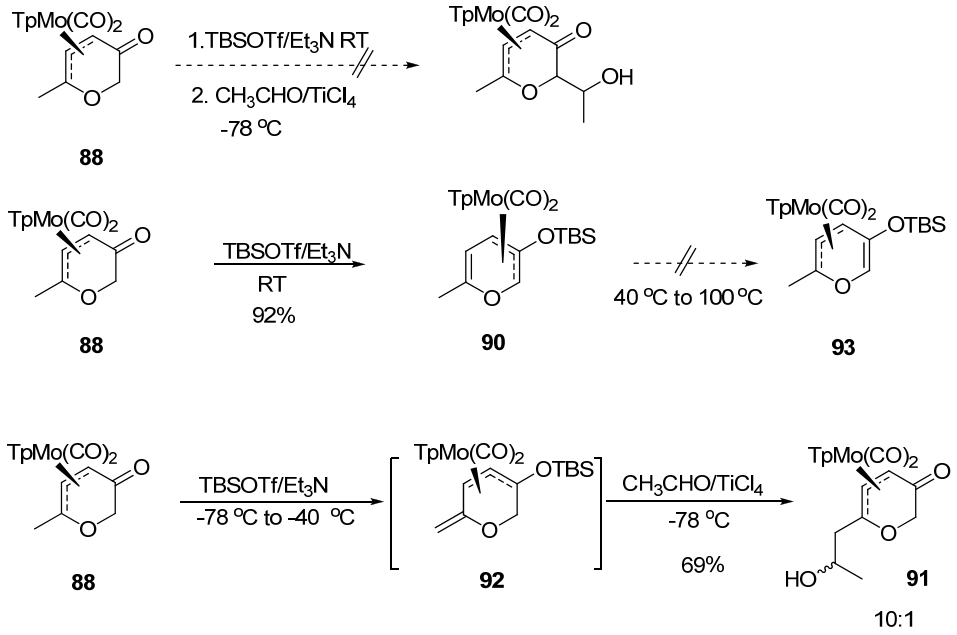
a) Starting from 98.7% ee (-)-**86**.

In contrast to 5-oxopyranyl complex **86**, 2-methyl-5-oxopyranyl complex **88** failed to give the desired Mukaiyama-aldol adducts under similar conditions. As a control experiment, the silyl enol ether was isolated in 92% yield in the first step (TBSOTf/Et_3N), and the structure was determined to be compound **90** (Scheme 31). Generation of the silyl

[50] This reaction was established and extensively studied by Dr. Heilam Wong and Dr. Yongqiang Zhang.
[51] Wong, H. Ph.D. Dissertation, Emory University, 2006.
[52] Dr. Yongqiang Zhang, Liebeskind's group research report, Emory University.

enol ether at low temperature (-78 ^{o}C to -40 ^{o}C) followed by addition of pre-mixed $TiCl_4$ and CH_3CHO (-78 ^{o}C) afforded the unexpected aldol adduct **91** which should derive from the condensation of silyl enol ether **92** and CH_3CHO. However, all attempts to isolate **92** were unsuccessful. It is assumed that **92** is the kinetically favored silyl enol ether form, which might easily isomerize to the thermodynamically more stable **90** at higher temperature. Compound **90** is stable, and didn't isomerize to complex **93** under thermal conditions (40 to 100 ^{o}C).

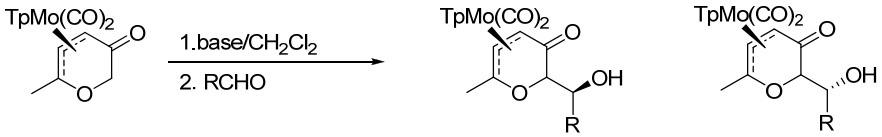
Scheme 31. Problems in Mukaiyama-aldol Reaction of 2-Methyl-5-Oxopyranyl Scaffold 88



As an alternative to a Mukaiyama-aldol reaction, it was found that complex **88** could be converted to hydroxyl compounds **89** through a traditional aldol reaction (Table 2). For aliphatic aldehydes, *anti*-isomers were the major adducts although no significant

diastereoselectivity was observed. The slight preference for *anti* selectivity could be rationalized by a chair-like transition state[53] (Figure 3, A). One crucial factor in this aldol reaction is the selection of solvent. Among different solvents that have been investigated, dichloromethane was the most efficient one in terms of yields. Other solvents, such as THF, dimethoxyethane and Et_2O, only gave low yields of products. Results of the aldol reaction of **88** with different bases under different conditions are summarized in Table 2.

Table 2. Aldol Reaction of 2-Methyl-5-Oxopyranyl Scaffold 88



88 *anti*-**89** *syn*-**89**

Entry	Ketone	Aldehyde	Temp (^oC)	Base	*anti*:*syn*	Yield (%)	% ee
1	(±)-**88**	acetaldehyde	- 78	LiHMDS	2:1	61, **89f**	
2	(±)-**88**	propaldehyde	- 78	LDA	5:1	36, **89g**	
3	(±)-**88**	propaldehyde	-78	LiHMDS	4:1	80, **89g**	
4	(±)-**88**	propaldehyde	-78	KHMDS	2:1	35, **89g**	
5	(±)-**88**	acrolein	-78	LiHMDS	1:2[a]	63, **89h**	
6	(-)-**88**	acrolein	- 90[b]	LiHMDS	1:3[a]	82, **89h**	98.7[e]

a) The *anti*/*syn* selectivity was determined by HPLC of crude product mixture.

b) MeOH/liquid N_2 bath; temperature was around -90 ^oC.

c) Starting from 98% ee (-)-**88**.

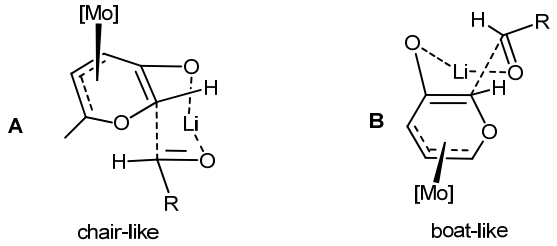
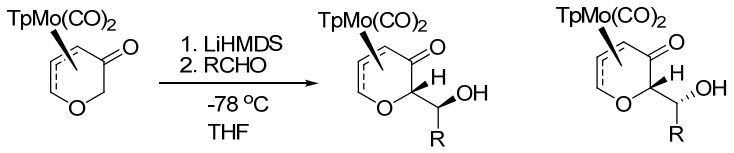


Figure 3. Plausible Transition States for Aldol Reaction of 88

[53] Zimmerman, H.E.; Traxler, M. D. *J. Am. Chem. Soc.* **1957**, *79*, 1920-1923.

It should be noted, unlike aliphatic aldehydes, acrolein displayed diastereoselectivity favoring the *syn*-isomer in the aldol reaction with **88** (Table 2, entries 5 and 6). Lower reaction temperature (-90 ^{o}C) could slightly increase the *syn* selectivity. Since the production of *syn* isomer from an *E*-enolate through a cyclic transition state implicates a boat-like transition state,[54] a possible transition state was proposed in Figure 3 (B). A similar trend was also reported for the aldol reaction of complex **86** with some α,β-unsaturated aldehydes (Table 3).[55] The *syn*-selective aldol reaction of pyranyl scaffolds **86** and **88** seems to be aldehyde dependent (α,β-unsaturated aldehydes); The reason behind remains unclear at this writing.

Table 3. *Syn*-selective Aldol Reaction of 5-Oxopyranyl Scaffold 86[55]



86 *anti* *syn*

Entry	Ketone	Aldehyde	Temp (^{o}C)	*anti*:*syn*	Yield (%)
1	(±)-**86**	acrolein	- 78	1:9	30
2	(±)-**86**	crotonaldehyde	- 78	3:7	33

Intramolecular '1,5-Michael-like' Reaction

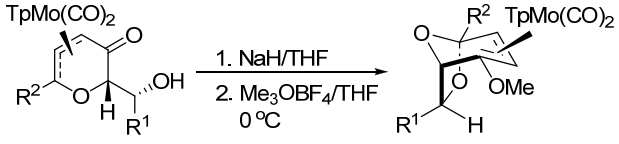
Treatment of *syn*-**89** or *anti*-**89** with NaH followed by Me_3OBF_4 quenching generated 1,5-Michael adducts *exo*-**94** and *endo*-**95** respectively in moderate to excellent yields as

[54] For examples of boat-like transition state in Aldol reaction, see: (a) Gennari, C.; Colombo, L.; Scolastico, C.; Todeschini, R. *Tetrahedron* **1984**, *40*, 4051-4058. (b) Denmark, S. E.; Wong, K-T.; Stavenger, R. A. *J. Am. Chem. Soc.* **1997**, *119*, 2333-2334.

[55] Dr. Yongqiang Zhang, Liebeskind's group research report, Emory University.

depicted in Table 4 and Table 5.[56] This novel transformation proceeds with complete facial diastereoselectivity which is caused by the attack of the internal alkoxide from the opposite face of the bulky $TpMo(CO)_2$ unit. The *exo* and *endo* relationship are determined by the stereochemistry of hydroxyl groups in **89**: *syn*-**89** afforded *exo* stereoisomers whereas *anti*-**89** afforded *endo* stereoisomers. This *exo*/*endo* relationship is confirmed by comparing the coupling constants between the hydrogen atoms adjacent to the bridging oxygen atoms and their vicinal neighbors. Normally, the coupling constant of the *exo* isomers are around 0-1 Hz, whereas the coupling constants of *endo* isomers are relatively larger, around 3.6 Hz.[57]

Table 4. Synthesis of *exo*-Intramolecular '1,5-Michael' Adducts

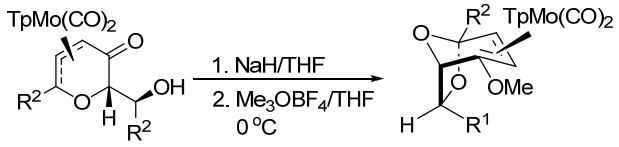


(±)-*syn*-**89** (±)-*exo*-**94**

Entry	*syn*-**89**	R^1	R^2	Yield (%)
1	(-)-**89a**	Me	H	93, **94a**
2	(±)-**89b**	Et	H	97, **94b**
3	(±)-**89f**	Me	Me	99, **94c**
4	(±)-**89g**	Et	Me	98, **94d**

[56] Among different solvents (CH_2Cl_2, THF, Et_2O, toluene) that have been investigated, THF gave the best yields.
[57] The *exo* and *endo* relationship are established previously by X-ray crystallographic analysis and NMR studies, see: Yin, J.; Liebeskind, L. S. *J. Am. Chem. Soc.* **1999**, *121*, 5811-5812.

Table 5. Synthesis of *endo*-Intramolecular '1,5-Michael' Adducts



(±)-*anti*-**89** (±)-*endo*-**95**

Entry	*anti*-**89**	R^1	R^2	Yield (%)
1	(-)-**89a**	Me	H	79, **95a**
2	(±)-**89f**	Me	Me	76, **95b**
3	(±)-**89g**	Et	Me	99, **95c**

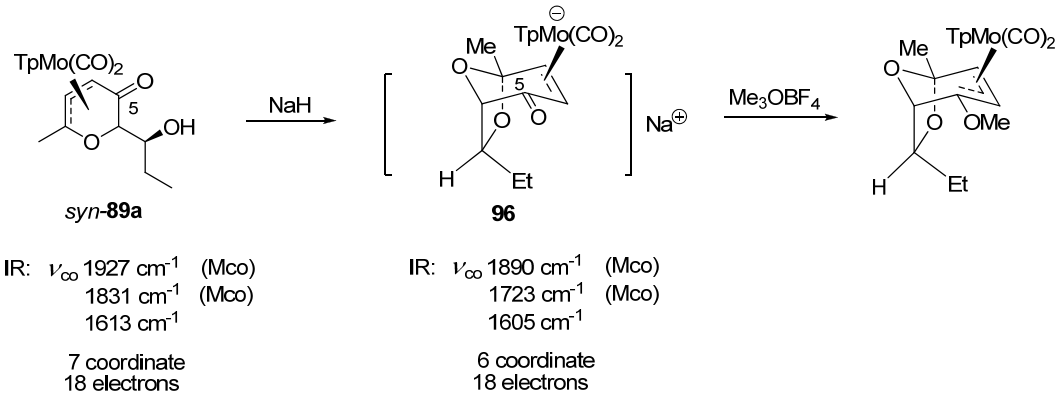
In this intramolecular 1,5-Michael-like reaction, *syn* aldol adducts gave faster reactions than their *anti* analogs. For the *syn* adducts, the reactions could be completed in 1 h. On the other hand, for the *anti* isomers, it normally took 5 hours to finish the reaction.

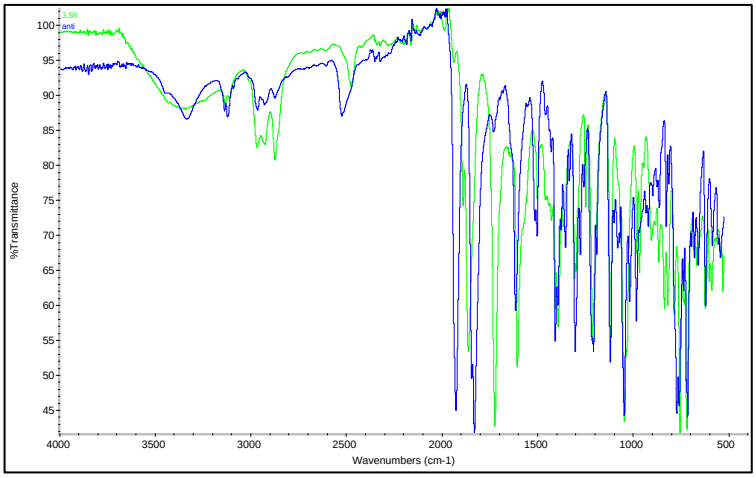
It is proposed that the '1,5-Michael-like reaction' is facilitated by the propensity of $TpMo(CO)_2$ moiety to favor 6-coordinate over 7 coordinate structures,[58] which would generate an anionic $TpMo(CO)_2$ intermediate **96** that possesses a good π-back-bonding enone ligand (Scheme 32). Infrared analysis of the '1,5-Michael-like' reaction of compound *syn*-**89a** provided evidence of the electron rich intermediate **96**. It was discovered that in the reaction mixture two metal carbonyl stretches shifted from 1927 cm^{-1} and 1831 cm^{-1} (*syn*-**89a**) to 1890cm^{-1} and 1723 cm^{-1} (reaction mixture) (Figure 4). The carbonyl stretch at C-5 also shifted from 1613 cm^{-1}(*syn*-**89a**) to 1605 cm^{-1} (reaction mixture). Since the wavenumber of carbonyl stretch reflects the available electron density

[58] Curtis, M. D.; Shiu, K. B.; Butler, W. M. *Organometallics* **1983**, *2*, 1475-1477.

on the metal (more electron density, smaller wave number),[59] it is indicated that an electron rich metal center was formed during the 1,5-Michael process. Further confirmation will be needed to verify this hypothesis, such as crystal structures of **96** with different counter ion.

Scheme 32. Plausible Mechanism for Intramolecular '1,5-Michael-like' Reaction





Blue--*syn*-**89a**
Green—reaction mixtue

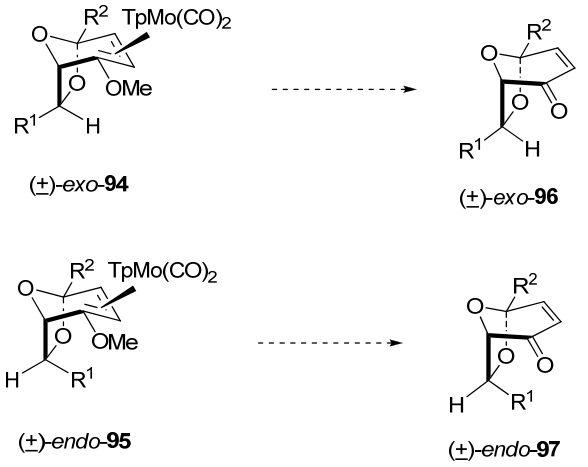
Figure 4. Infrared Spectra of *Syn*-89a and '1,5-Michael' Reaction Mixture

[59] Lambert, J. B.; Shurvell, H. F.; Cooks, R. G. *Organic Structural Spectroscopy*; Prentice Hall: New Jersy, 1998; p 183-184.

Intramolecular '1,5-Michael-demetalation' cascade

After completion of the study of intramolecular '1,5-Michael-like' reaction, the demetalation study of 6,8-dioxabicyclo[3.2.1]octenyl molybdenum complexes *exo*-**94** and *endo*-**95** to their corresponding enones was carried out (Scheme 33).

Scheme 33. Expected Demetalation of 6,8-Dioxabicyclo[3.2.1]octenyl Molybdenum Complexes

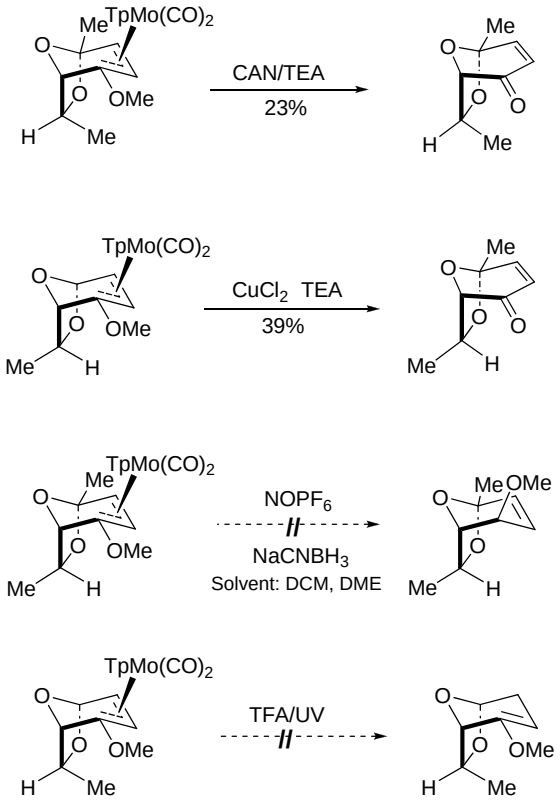


Although oxidative demetalation with cerium(IV) ammonium nitrate or $CuCl_2$ were demonstrated very effective in the decomplexation of various molybdenum complexes containing a terminal methoxy group in the π-allyl unit,[41a,41c,42] demetalation of the 6,8-dioxabicyclo[3.2.1]octenyl molybdenum complexes under similar conditions only afforded the desired enones in low yields without recovery of starting materials (Scheme 34). Other demetalation protocols,[60] including photolytic protodemetalation (TFA/UV) and reductive demetalation ($NOPF_6$ followed by $NaCNBH_3$), were also not able to

[60] Moretto, A. F.; Liebeskind, L. S. *J. Org. Chem.* **2000**, *65*, 7445-7455.

provide the desired products.

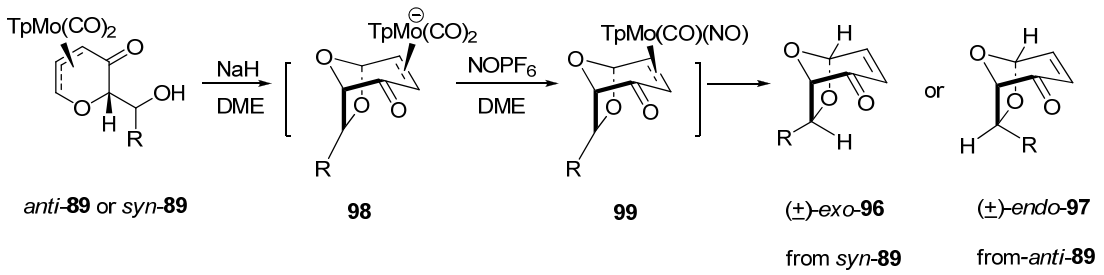
Scheme 34. Attempts of Demetalation of 6,8-Dioxabicyclo[3.2.1]octenyl Molybdenum Complexes



Considering that 1,5-Michael-like reactions go through an η^2 anionic $TpMo(CO)_2$ intermediate (Scheme 35, compound **98**), a novel '1,5-Michael reaction-demetalation' cascade was developed as shown in Scheme 35. Quenching 1,5-Michael intermediate **98** with $NOPF_6$ afforded unstable η^2-complexes **99** which could undergo spontaneous decomplexation to afford the desired bicyclic enones.[61]

[61] Dimethoxyethane was employed as solvent in this reaction. Comparing to THF, intramolecular 1,5-Michael reaction proceeds slowly in DME. However, it seemed the $TpMo(CO)_2$ moiety in the η^2 intermediate was easier to dissociate in DME than in THF.

Scheme 35. Mechanism of 1,5-Michael Reaction-Demetalation Cascade



The formation of the η^2 $TpMo(CO)_2$ intermediate **99** was confirmed by isolation and characterization of η^2-complex **100**[62] (Figure 5). The assigned structure of **100** is consistent with its spectroscopic data. ^{13}C NMR of **100** confirmed a carbonyl shift at 204.0 ppm. Infrared analysis revealed the NO stretching band at 1679 cm^{-1}. Meanwhile, the metal carbonyl shifted to 2011 cm^{-1} which also indicates the presence of NO. High resolution mass spectra also confirmed the composition of **100**.

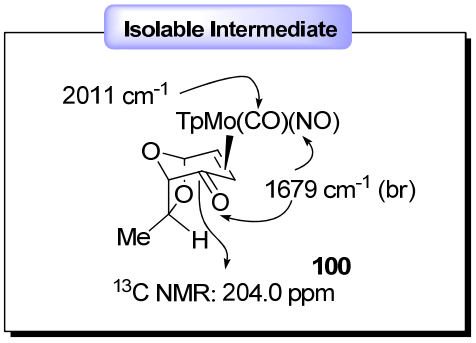


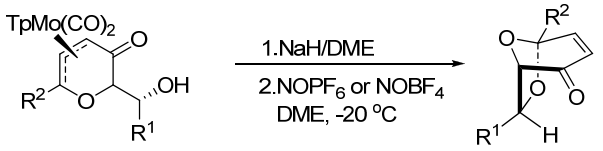
Figure 5. Spectroscopic Evidence of η^2-complex 100

This novel one-pot '1,5-Michael-like reaction-demetalation' sequence efficiently

[62] When using THF as solvent, complex **100** was isolated in 45% yield as a bright yellow solid. Only less than 5% enone was isolated in this reaction.

combines 1,5-Michael reaction with decomplexation, and provides a rapid access to the 6,8-dioxabicyclo[3.2.1]octane skeleton in only 2 steps from parent scaffolds **86** and **88.** The scope of the 1,5-Michael-reation-demetalation cascade is depicted in Table 6 and Table 7. It was demonstrated that this sequence proceeded with no detectable enantiopurity loss when carried out with chiral, non-racemic molybdenum complexes (-)-*syn*-**89a** and (-)-*anti*-**89a**. For example, both (-)-(1*S*,5*S*,7*R*)-7-methyl-6,8-dioxabicyclo [3.2.1]oct-3-en-2-one (*exo*-**96a)** (Table 6, entry 1) and (-)-(1*R*,5*R*,7*S*)-7-methyl-6,8-dioxabicyclo[3.2.1]oct-3-en-2-one (*endo*-**97a)** (Table 7, entry 4) were prepared in 98.7% ee.

Table 6. Synthesis of *exo*-6,8-Dioxabicyclo[3.2.1]oct-3-en-2-ones[a]



syn-**89** *exo*-**96**

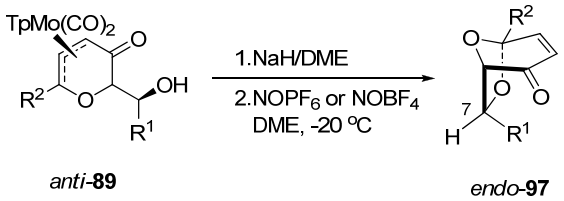
Entry	*syn*-**89**	R^1	R^2	% Yield	% ee
1	(-)-**89a**	Me	H	80, **96a**	98.7[b]
2	(±)-**89c**	*E*-prop-1-enyl	H	56, **96b**	-
3	(±)-**89d**	phenyl	H	56, **96c**	-
4	(±)-**89e**	3-$NO_2C_6H_4$	H	21, **96d**[c]	-
5	(±)-**89g**	Et	Me	73, **96e**	-

a) $NOPF_6$ and $NOBF_4$ were equal effective in this reaction.

b) Starting from 98.7% ee (-)-*syn*-**89a**.

c) Preliminary result.

Table 7. Synthesis of *endo*-6,8-Dioxabicyclo[3.2.1]oct-3-en-2-one[a]



anti-**89** *endo*-**97**

Entry	*anti*-**89**	R^1	R^2	Yield (%)	% ee
1	(-)-**89a**	Me	H	70, **97a**	98.7[b]
2	(±)-**89c**	*E*-prop-1-enyl	H	44, **97b**	-
3	(±)-**89d**	phenyl	H	61, **97c**[c]	-
4	(±)-**89g**	Et	Me	66, **97d**	-

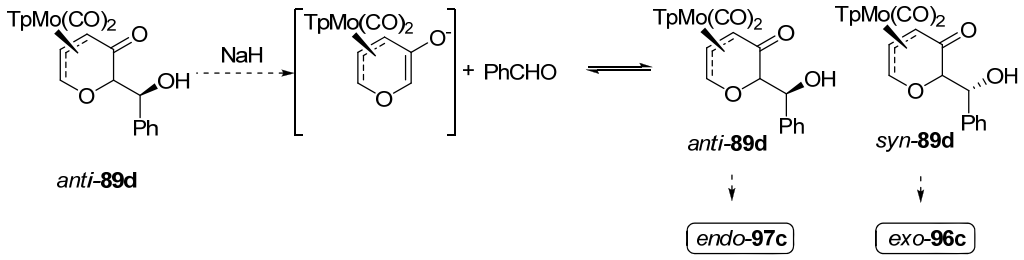
a) $NOPF_6$ and $NOBF_4$ were equal effective in this reaction.

b) Starting from 98.7% ee (-)-*anti*-**89a**.

c) Epimerization was observed at C7 (*exo*:*endo* 3:10).

The epimerization of at C-7 in **97c** (Table 7, entry 3) might be due to a retro-aldol reaction of *anti*-**89d** followed by another aldol reaction (Scheme 36). The resulting *syn*-**89d** could be further converted to *exo*-**96c** *via* '1,5-Michael-demetalation' reaction.

Scheme 36. Possible Epimerization Mechanism



Total synthesis of (+)-(1*R*,2*S*,5*S*,7*R*)-2-Hydroxy-*exo*-Brevicomin

Alkylated 6,8-dioxabicyclo[3.2.1]octane skeletons represent the basic structure of a series

of bark beetle pheromones such as *exo*-brevicomin[63] and frontalin[64] (Figure 6). These pheromones play a major role in the communication systems of different beetles.[65] In 1996, Francke and co-workers[66] isolated and identified several new hydroxylated brevicomin derivatives from male mountain pine beetles, *Dendroctounus ponderosae*. As an application of the intramolecular '1,5-Michael-like' reaction, the enantiocontrolled synthesis of (+)-(1*R*,2*S*,5*S*,7*R*)-2-hydroxy-*exo*-brevicomin was investigated.

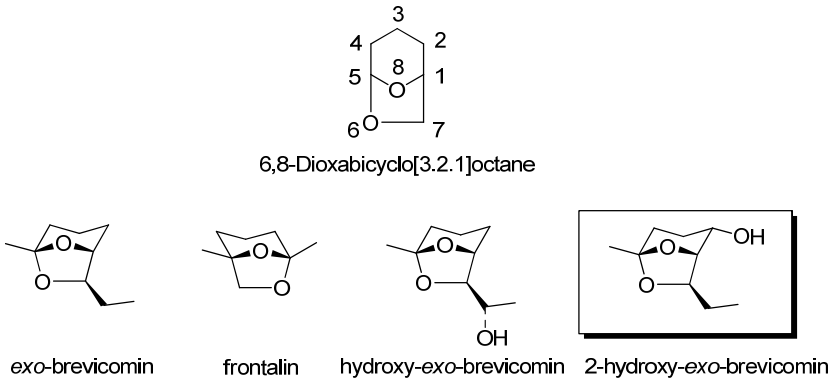


Figure 6. 6,8-Dioxabicyclo[3.2.1]octanes

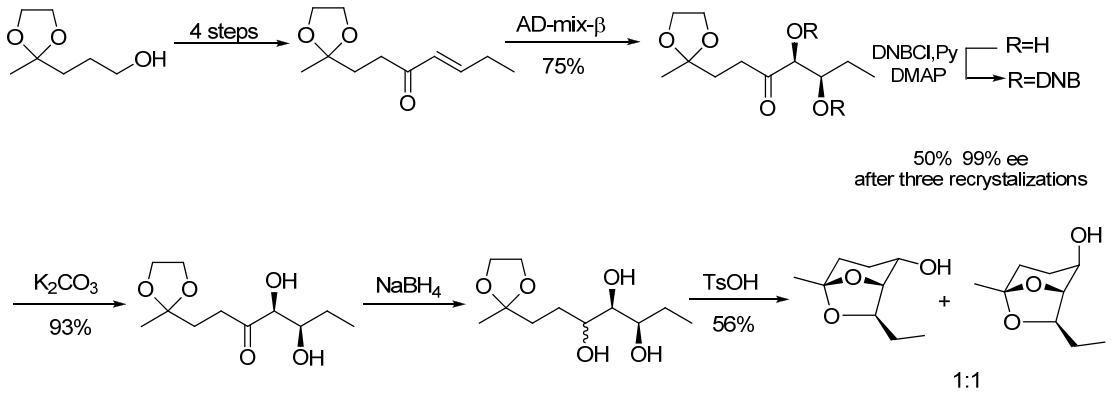
The synthesis of alkylated 6,8-dioxabicyclo[3.2.1]octane skeletons has received continual attention[65, 67, 68] during the past decades due to the important bioactivities (insect pheromones) of molecules possessing this structural unit. Moreover, research shows that only one single enantiomer is bioactive[69] in 60% percent of those chiral pheromones. For

[63] Silverstein, R. M.; Brownlee, R. G.; Bellas, T. S. *Science* **1968**, *159*, 889-891.
[64] Kinzer, G. W.; Fentiman, A. F. Jr.; Page, T. F. Jr.; Foltz, R. L.; Vite, J. P.; Pitman, G. B. *Nature* **1969**, *221*, 477-478.
[65] Frank, W.; Schröder, W. *Curr. Org. Chem.* **1999**, *3*, 407-443.
[66] Francke, W.; Schröder, F.; Philipp, P.; Meyer, H.; Sinnwell, V.; Gries, *F. Bioorg. Med. Chem.* **1996**, *4*, 363-374.
[67] Mundy, B. P.; Lipkowitz, K. B.; Dirks, G. W. *Heterocycles* **1977**, *6*, 51-76.
[68] Jun, J.-G. *Synlett* **2003**, *12*, 1759-1777.
[69] Mori, K. *Eur. J. Org. Chem.* **1998**, 1479-1489.

example, only (+)-*exo*-brevicomin was found to be the bioactive enantiomer.[70] Therefore, enantiocontrolled syntheses of these molecules are more important than their racemic forms.

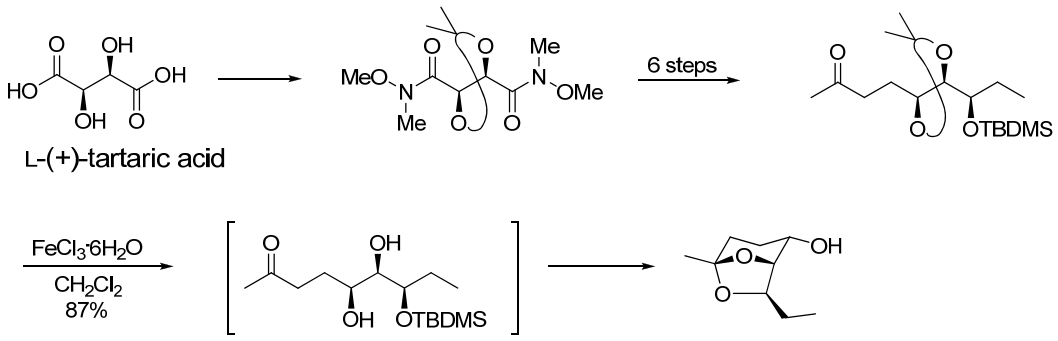
Among various synthetic approaches to alkylated 6,8-dioxabicyclo[3.2.1]octane skeletons, the most commonly used method is intramolecular ketalization, which involves asymmetric dihydroxylation or epoxidation. To date, there are two total syntheses of (+)-(1*R*,2*S*,5*S*,7*R*)-2-hydroxy-*exo*-brevicomin reported respectively by the Mori[71] (Scheme 37) and Prasad groups[72] (Scheme 38). Both of them featured the intramolecular ketalization as the key step.

Scheme 37. Mori's Total Synthesis of (+)-(1*R*,2*S*,5*S*,7*R*)-2-Hydroxy-*exo*-Brevicomin



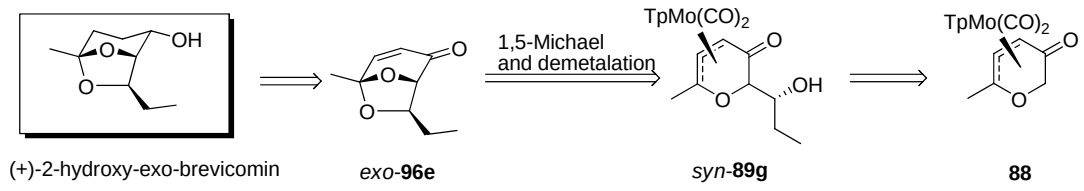
[70] Wood, D. L.; Browne, L. E.; Ewing, B.; Lindahl, K.; Bedard, W. D.; Tilden, P. E.; Mori, K.; Pitman, G. B.; Hughes, P. R. *Science* **1976**, *192*, 896-898.
[71] Takikawa, H.; Shimbo, K-I.; Mori, K. *Liebigs Ann.***1997**, 821-824.
[72] Prasad, K. R.; Anbarasan, P. *Synlett* **2006**, *13*, 2087-2088.

Scheme 38. Prasad's Total Synthesis of (+)-(1*R*,2*S*,5*S*,7*R*)-2-Hydroxy-*exo*-Brevicomin



Our retrosynthetic analysis of (+)-(1*R*,2*S*,5*S*,7*R*)-2-hydroxy-*exo*-brevicomin is outlined in Scheme 39. It was envisioned that (+)-(1*R*,2*S*,5*S*,7*R*)-2-hydroxy-*exo*-brevicomin could be derived from dioxabicylic enone *exo*-**96e** which was the intramolecular '1,5-Michael-demetalation' adduct of molybdenum complex *syn*-**89g**. Complex s*yn*-**89g** could be synthesized from 2-methyl-5-oxopyranyl scaffold **88** *via* traditional aldol reaction. If successful, this enantiomeric organometallic scaffold strategy should provide a novel and concise assembly of (+)-(1*R*,2*S*,5*S*,7*R*)-2-hydroxy-*exo*-brevicomin with full stereocontrol.

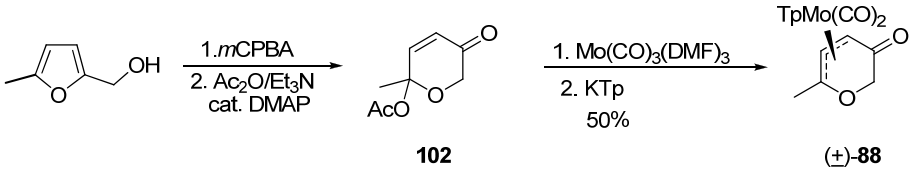
Scheme 39. Retrosynthetic Analysis of (+)-(1*R*,2*S*,5*S*,7*R*)-2-Hydroxy-*exo*-Brevicomin



Racemic 2-methyl-5-oxopyranyl scaffold **88** was synthesized from 5-methyl-2-furanmethanol *via* sequential Achmatowicz rearrangement, acetylation of the

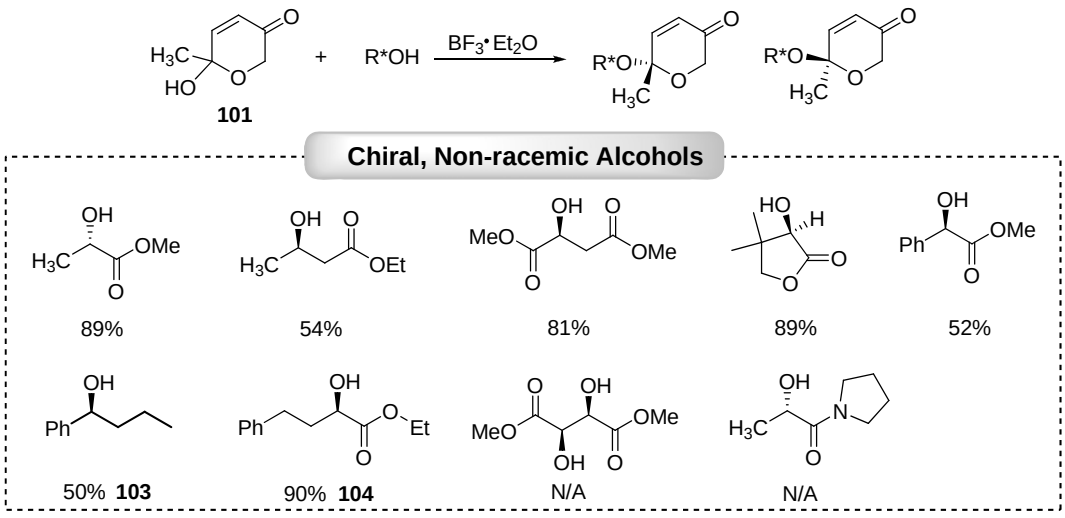
corresponding alcohol, complexation with $(DMF)_3Mo(CO)_3$ and subsequent ligand exchange with KTp (Scheme 40).[45]

Scheme 40. Synthesis of Racemic 2-Methy-5-oxopyranyl Scaffold 88



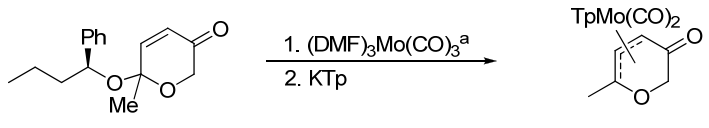
$BF_3{\cdot}Et_2O$ mediated diastereomer formation of **101** with different commercially available chiral, non-racemic alcohols (Scheme 41) led to the formation of various diastereomeric 6-alkoxypyranones in good to excellent yields. However, only (*S*)-1-phenyl butanol and ethyl (*R*)-2-hydroxy-4-phenylbutyrate substituted pyranone **103** and **104** could be resolved by column chromatography.

Scheme 41. Diastereomer Formation of 101 with Different Non-racemic Alcohols



Complexation of **103a** [73] (faster eluting diastereomer, > 99% ee) with 2 equiv $(DMF)_3Mo(CO)_3$ at -40 °C to room temperature only afforded 2-methyl-5-oxopyranyl scaffold **88** in 1.8% ee (Scheme 42). Presumably, the benzylic alkoxide and the methyl group in **103** exhibit similar steric effect on the dihydropyran ring which allows the Mo(0) to approach the enone from both sides of the ring, thus importing no facial selectivity compared with substrate **87A** and **87B** (Scheme 30).

Scheme 42. Complexation with 103a



103a
fast eluting diastereoisomer
>99% ee

1.8% ee

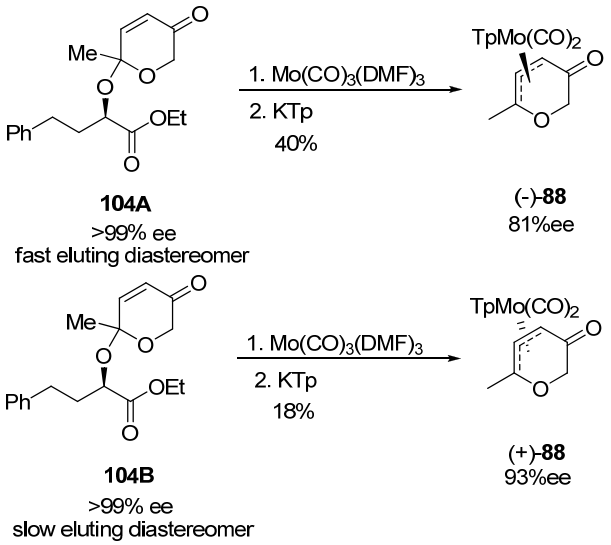
a) 2 equiv $(DMF)_3Mo(CO)_3$ at -40 °C to 0 °C, 1.5 h / KTp, 1 h at rt

Gratifyingly, complexation of **104a** (faster eluting diastereomer)[74] and **104b** (slower eluting diastereomer) with low concentrations of $(DMF)_3Mo(CO)_3$ in dichloromethane provided 2-methyl-5-oxopyranyl scaffold **88** with moderate ee. In order to improve the ee, the complexation conditions had been extensively studied. After optimization,[75] complexation of **104a** afforded (-)-2-methyl-5-oxopyranyl scaffold **88**[76] in 40% yield and 81% ee, whereas **104b** afforded (+)-**88** in 18% yield and 93% ee (Scheme 43). The

[73] The absolute configuration of **103A** is unknown.
[74] The absolute configuration of **104a** and **104b** are unknown at this writing.
[75] Following methods listed in: Ward, Y. D.; Villanueva, L. A.; Allred, G. D.; Liebeskind, L. S. *J. Am. Chem. Soc.* **1996**, *118*, 897-898.
[76] The absolute configuration was determined later by the total synthesis of (+)-(1*R*,2*S*,5*S*,7*R*)-2-hydroxy-*exo*-brevicomin *via* (-)-**88**.

enantiopurity of (-)-**88** can be increased to > 98% ee after recrystallization[77] in dichloromethane and hexanes.

Scheme 43. Synthesis of Chiral, Non-racemic 88



Selected examples of different conditions (concentration, temperature, addition sequence, reaction time and solvents) explored in the enantiocontrolled complexation are shown in Table 8. At low concentrations of both $(DMF)_3Mo(CO)_3$ and **104**, the complexation of **104a** and **104b** provided moderate yields and reproducible ee (> 80% ee). To achieve higher yields, dichloromethane involved in this reaction should be freshly dried and degassed.

[77] (-)-**88** tends to crystallize as a single enantiomer.

Table 8. Selected Conditions in the Synthesis of Chiral, Non-racemic 88

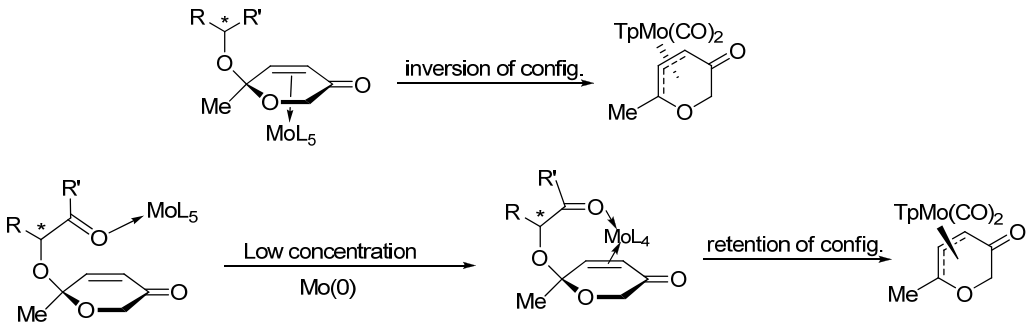
Entry	SM	solvent	Time A[a]	Time B[b]	Concn of Mo(0)[c]	Concn of SM	Yield (%)	% ee
1	**104a**	DCM	-[j]	24 h	0.62 (0,83 eq.)[d,f]	0.75	24	83.5
2	**104b**	DCM	-[j]	4 d	0.16 (0,91 eq.)[d,f]	0.18	22	33.5
3	**104a**	THF	-[j]	24 h	0.043 (0.7 eq.)[e]	0.33[g]	30	9
4	**104b**	DCM	10 min	30 min	0.037(0.81 eq)[e]	0.091	28	79.1
5	**104b**	DCM	20 min	30 min	$7.4x10^{-3}$(0.64 eq.)[e]	0.017[h]	45	85.1
6	**104a**	DCM	25 min	1 h	$8.8x10^{-3}$(0.70 eq.)[e]	0.018 [h]	24	87
7	**104a**	DCM	45 min	1 h	$9.7x10^{-3}$(0.65 eq.)[e]	0.022 [h]	40[i]	81
8	**104b**	DCM	30 min	1 h	$8.2x10^{-3}$(0.65 eq.)[e]	0.018 [h]	18	93.1

a) The addition time of Mo(0) to SM; b) Time after the addition of Mo(0); c) 1 equiv of SM; d) $(Tol)Mo(CO)_3$ as Mo(0) source; e) $(DMF)_3Mo(CO)_3$ as Mo(0) source; f) $(Tol)Mo(CO)_3$ was added as a solid to a solution of SM; g) A solution of of SM in THF was added a solution of $(DMF)_3Mo(CO)_3$ in THF; h) A solution of $(DMF)_3Mo(CO)_3$ at -78 ^oC in DCM was added dropwise to a solution of SM in DCM at rt *via* cannula; i) Yield based on recovery of SM is 69%. j) Addition of SM into Mo(0) solution.

According to a previous study,[48] two possible mechanisms are shown in Scheme 44 to rationalize this enantiocontrolled complexation. First, the bulky alkoxy group might cause the addition of Mo(0) from its opposite face and lead to inversion of configuration in the oxidative addition step. It is also possible that Mo(0) could first coordinate to the carbonyl group, then be delivered to the same face as the alkoxy group (retention addition). Given the fact that the absolute configurations[78] of **104a** and **104b** haven't been confirmed yet, the exact mechanism is still under investigation.

[78] Efforts are still underway to determine the absolute configurations of **104A** and **104B**.

Scheme 44. Possible Mechanism for the Synthesis of Chiral, Non-racemic 88

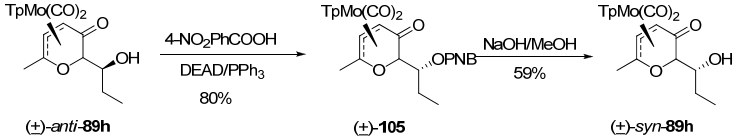


Having the enantiomeric (-)-**88** in hand, the synthesis of (+)-(1*R*,2*S*,5*S*,7*R*)-2-hydroxy-*exo*-brevicomin is detailed in Scheme 45. Aldol reaction of 98% ee (-)-**88** with acrolein[79] furnished *syn* and *anti*-**89h** in 82% yield (*syn* : *anti* = 3:1, HPLC). Since *syn* and *anti*-**89h** are inseparable by simple column chromatography on silica gel, the mixture of *syn* and *anti*-**89h** was directly converted to *syn* and *anti*-**89g**[80] by Pd catalyzed hydrogenation in 91% yield and 98% ee. Following the 1,5-Michael-demetalation protocol, (-)-*syn*-**89g** was transformed to bicyclic acetal **96e** in 73% yield (98% ee) which experienced smooth hydrogenation to afford ketone **106** in 80% yield. Finally, reduction of the carbonyl with $NaBH_4$ accomplished the synthesis of (+)-(1*R*,2*S*,5*S*,7*R*)-2-hydroxy-*exo*-brevicomin **107** in 82% yield ($[\alpha]_D^{20}$ = +40.3 , *c* = 1.10, $CHCl_3$, Lit.[71] $[\alpha]_D^{24}$ = +33.3, *c* = 1.94, $CHCl_3$,). The spectroscopic properties of compound (+)-**107** are in full accordance with those of the natural product.[71,72]

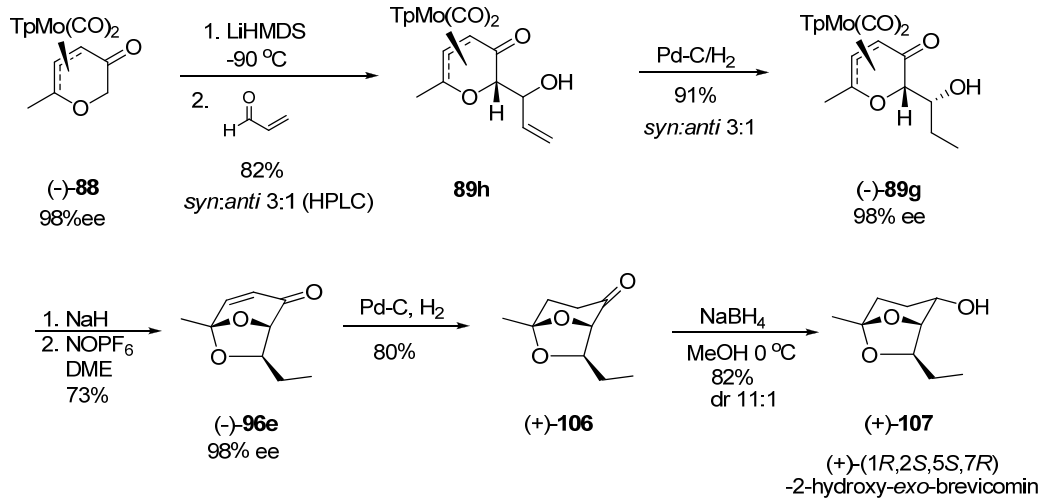
---

[79] Acrolein was intentionally selected instead of propaldehyde for its higher *syn* selectivity in Aldol reaction.

[80] *Anti*-**89h** can be converted to *syn*-**89h** by Mitsunobu reaction.



Scheme 45. Enantiocontrolled Total Synthesis of (+)-(1*R*,2*S*,5*S*,7*R*)-2-hydroxy-*exo*-brevicomin



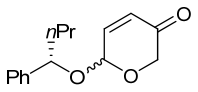
Conclusion

Neutral TpMo(CO)$_2$(η^3-pyranyl) scaffolds bearing an internal alkoxide underwent a novel intramolecular '1,5-Michael-like' reaction. Through a one-pot '1,5-Michael-decomplexation' sequence, 6,8-dioxabicyclo[3.2.1]oct-3-en-2-one frame work can be easily accessed in good to excellent yields with high enantiopurity. A total synthesis of (+)-(1*R*,2*S*,5*S*,7*R*)-2-hydroxy-*exo*-brevicomin was accomplished to showcase this novel transformation.

Experimental Section

General Methods. Unless otherwise indicated, all ^{1}H and ^{13}C NMR spectra were recorded on a Varian Inova 400 MHz (400 MHz ^{1}H, 100 MHz ^{13}C) or Varian Inova 600 MHz (600 MHz ^{1}H, 150 MHz ^{13}C) at room temperature in $CDCl_3$, CD_2Cl_2, C_6D_6 or acetone-*d*6. Spectra were internally referenced to $CDCl_3$ (7.26 ppm for H^1 and 77.0 ppm for ^{13}C), CD_2Cl_2 (5.31 ppm for H^1 and 53.8 ppm for ^{13}C), C_6D_6 (7.16 ppm for H^1 and 128.0 ppm for ^{13}C) or acetone-d_6 (2.05 ppm for H^1 and 29.8 ppm for ^{13}C). IR spectra were recorded on ASI React-IR® 1000 FT-IR spectrometer, equipped with a silicon probe or a Nicolet 380 FT-IR with a Smart Orbit diamond crystal plate. Peaks are reported (cm^{-1}) with the following relative intensities: s (strong, 67-100%), m (medium, 40-67%), w (weak, 20-40%) and br (broad). *Since almost all of the Tp molybdenum complexes decompose at about 180-200 ºC melting points are not significant and are not shown in the experimental section*. Analytical thin-layer chromatography (TLC) was carried out on commercial Merck aluminum back silica gel plates (silica gel 60 F_{254}, thickness: 200 μm) with fluorescent indicator (F-254). Optical rotations were measured Perkin-Elmer 241MC or Perkin-Elmer Model 341 polarimeters. Visualization was accomplished by UV light, stained with 5% phosphomolybdic acid (PMA) in ethanol or with ceric ammonium molybdate water solution. Column chromatography was performed on 60-230 Mesh silica gel (Silicycle or Merck). Unless otherwise specified, all solvents are dried over 4Å molecular sieves, titrated for water level with a Fisher Coulomatic K-F titrator before

using, and degassed by bubbling through argon or nitrogen for 10 minutes or dispensed and used directly from a Seca Solvent System purchased from Glass Contour. All reactions were carried out under a nitrogen or argon atmosphere, and all reaction flasks were flamed or oven dried prior to use.



87a and **87b**

[(*S*)-1-Phenyl-butoxy]-6*H*-pyran-3-one, 87a and **[(*S*)-1-Phenyl-butoxy]-6*H*-pyran-3-one, 87b**

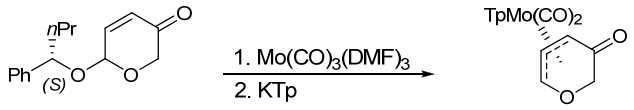
To a 250-mL flask charged with 2-acetoxy-5-oxo-5,6-dihydro-2*H*-pyran, **85** (4.0 g, 25.6 mmol, 1 equiv) and (*S*)-(-)-1-phenyl-1-butanol[81] (98% ee, 3.85 g, 25.6 mmol, 1 equiv) in CH_2Cl_2 (30 mL) under argon was added $ZnCl_2$ (1.0 M in Et_2O, 7.7 mL, 7.7 mmol, 0.3 equiv). The solution was stirred at room temperature for 67 hours, after which TLC indicated no starting material was left. The mixture was transferred into a separatory funnel containing H_2O (50 mL) and CH_2Cl_2 (50 mL). The organic layer was collected, washed with brine (50 mL), dried over $MgSO_4$, filtered, and concentrated. The crude material was further purified by column chromatography on silica gel (10% EtOAc in hexanes) to afford the less polar diastereomer **87a** (1.8 g, 29%), and more polar diastereomer **87b** (3.2 g, 51%) as colorless liquids.

87a: TLC (R_f = 0.66 hexanes-EtOAc 4:1). $[\alpha]_D^{20}$ = -90.1 (*c* = 0.75, CH_2Cl_2). IR

[81] (*S*)-(-)-1-phenyl-1-butanol was purchsed from Fluka, and used directly.

(cm^{-1}): 2961 (m), 2934 (m), 2871 (m), 1702 (s), 1455 (m), 1397(s), 1262(s). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.34 (m, 5H), 6.76 (dd, *J* = 10.2 Hz, 3.4 Hz, 1H), 6.12 (d, *J* = 10.0 Hz, 1H), 5.00 (d, *J* = 3.2 Hz, 1H), 4.76 (dd, *J* = 8.0 Hz, 5.6 Hz, 1H), 4.56 (d, *J* = 16.8 Hz, 1H), 4.12 (d, *J* = 16.8 Hz, 1H), 1.88 (m, 1H), 1.66 (m, 1H), 1.47 (m, 1H), 1.32 (m, 1H), 0.93 (t, *J* = 7.4 Hz, 3H). ^{13}C NMR (150 MHz, $CDCl_3$): δ 194.9, 144.8, 141.4, 128.6, 128.6, 128.0, 127.6, 126.9, 126.9, 89.9, 79.2, 66.4, 40.1, 19.3, 13.8. HRMS (ESI) Calcd for $C_{15}H_{19}O_3$ ($[M + H]^+$): 247.1329. Found: 247.1326.

87b: TLC (R_f = 0.57 hexanes-EtOAc 4:1). $[\alpha]_D^{20}$ = -113.3 (*c* = 0.444, CH_2Cl_2). IR (cm^{-1}): 2961 (m), 2934 (m), 2876 (m), 1702 (s), 1455 (m), 1393(s), 1262(s). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.30 (m, 5H), 6.93 (dd, *J* = 10.2 Hz, 3.4 Hz, 1H), 6.12 (d, *J* = 10.4 Hz, 1H), 5.39 (d, *J* = 3.2 Hz, 1H), 4.59 (t, *J* = 6.8 Hz, 1H), 3.95 (d, *J* = 17.2 Hz, 1H), 3.72 (d, *J* = 17.2 Hz, 1H), 1.88 (m, 1H), 1.72 (m, 1H), 1.32 (m, 2H), 0.93 (t, *J* = 7.4 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 195.0, 144.1, 142.4, 128.3, 128.3, 127.7, 127.6, 126.4(2), 93.4, 82.3, 66.1, 39.3, 18.9, 13.9. HRMS (ESI) Calcd for $C_{15}H_{19}O_3$ $[M + H]^+$: 247.1329. Found: 247.1336.



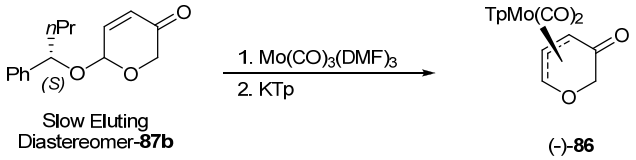
Fast Eluting Diastereomer-**87a** (+)-**86**

(+)-Dicarbonyl[hydridotris(1-pyrazolyl)borato][(2*R*)-(*η*-2,3,4)-5-oxo-5,6-dihydro-2*H*-pyran-2-yl]molybdenum, (+)-**86**

To a Schlenk flask charged with a solution of $Mo(CO)_3(DMF)_3$ (7.52 g, 18.80 mmol, 2 equiv) in degassed dry CH_2Cl_2 (40 mL) under argon at -40 ^oC was slowly added a solution of **87a** (2.32 g, 9.42 mmol, 1 equiv) in degassed CH_2Cl_2 (10 mL) . The reaction mixture was allowed to warm up to -20 ^oC over 1 hour, and then warmed to -10 ^oC over 30 min. The reaction was warmed to 0 ^oC and stirred for 2 hours before allowing the reaction to warm to room temperature over 30 min. Solid potassium hydridotris(1-pyrazolyl)borate (KTp) (5.22 g, 20.70 mmol, 2.2 equiv) was added in one portion and the reaction was stirred for 1 hour at room temperature. The solution was then passed through a pad of silica gel, eluting with EtOAc. Solvents were completely removed on a rotary evaporator, and the residue was further purified by column chromatography on silica gel (hexanes-EtOAc 1:1) to afford a yellow solid (+)-**86** (2.1 g, 48%) in 98.9% ee. *This compound tends to crystallize as a racemate, and therefore slow crystallization in hexanes/CH_2Cl_2 afforded the product in >99% ee when the first few crystals that formed were removed, and the filtrate was collected and dried under vacuum.*

*Characterization (+)-**86** can be found in reference 41a.*

(+)-**86**: $[\alpha]_D^{20}$ = +447.8 (*c* = 0.090, CH_2Cl_2). HPLC: CHIRALPAK AS-RH column, CH_3CN : H_2O = 55 : 45, 1.0 mL/min., λ = 254 nm, t_R = 11.43 min, >99% ee.

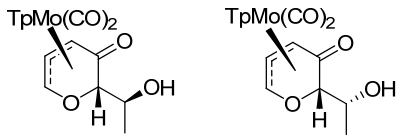


(-)-Dicarbonyl[hydridotris(1-pyrazolyl)borato][(2*S*)-η-(2,3,4)-5-oxo-5,6-dihydro-2*H*-pyran-2-yl]molybdenum, (-)-**86**

To a Schlenk flask charged with a solution of $Mo(CO)_3(DMF)_3$ (4.63 g, 11.6 mmol, 2 equiv) in degassed, dry CH_2Cl_2 (30 mL) under argon at -40 ^oC was slowly added a solution of **87b** (1.43 g, 5.80 mmol, 1 equiv) in degassed CH_2Cl_2 (10 mL) . The reaction mixture was allowed to warm up to -20 ^oC over 1 hour, and then warmed to 0 ^oC over 30 min. After the reaction was slowly warmed to room temperature over 30 min, solid potassium hydridotris(1-pyrazolyl)borate (KTp) (3.22 g, 12.77 mmol, 2.2 equiv) was added in one portion. After stirring for 1 hour at room temperature, the solution was passed through a pad of silica gel, eluting with EtOAc. The solvents were completely removed on a rotary evaporator, and the residue was further purified by column chromatography on silica gel (hexanes-EtOAc 1:1) to afford a yellow solid product (-)-**86** (1.64 g, 61%) in 97.6% ee. *This compound tends to crystallize as a racemate, and therefore slow crystallization in hexanes/CH_2Cl_2 afforded the product in >99% ee when the first few crystals that formed were removed, and the filtrate was collected and dried under vacuum.*

*Characterization (-)-**86** can be found in reference 41a.*

(-)-**86**: $[\alpha]_D^{20}$ = -525.8 (*c* = 0.095, CH_2Cl_2). HPLC: CHIRALPAK AS-RH column, CH_3CN : H_2O = 55 : 45, 1.0 mL/min., λ = 254 nm, t_R = 14.62 min, >99% ee.



(-)-*anti*-**89a** (-)-*syn*-**89a**

(-)-Dicarbonyl[hydridotris(1-pyrazolyl)borato]{(2*S*,6*S*)-(η-2,3,4)-6-[(*S*)-1-hydroxylethyl]-5-oxo-5,6-dihydro-2*H*-pyran-2-yl}molybdenum, (-)-*anti*-89a and **(-)-Dicarbonyl[hydridotris(1-pyrazolyl)borato]{(2*S*,6*S*)-η-(2,3,4)-6-[(*R*)-1-hydroxylethyl]-5-oxo-5,6-dihydro-2*H*-pyran-2-yl}molybdenum, (-)-*syn*-89a.**

To a Schlenk flask charged with a solution of (-)-**86** (540 mg, 98.7% ee, 1.17 mmol, 1 equiv) in CH_2Cl_2 (10 mL) was successively added Et_3N (0.19 mL, 1.35 mmol, 1.15 equiv) and TBSOTf (0.31 mL, 1.35 mmol, 1.15 equiv). The reaction mixture was stirred for 30 min at room temperature, then cooled down to -78 ºC. To this mixture was slowly added a low-temperature (-78 ºC) premixed solution of acetaldehyde (92 μL, 1.64 mmol, 1.4 equiv) and $TiCl_4$ (1.0 M in CH_2Cl_2, 1.52 mL, 1.52 mmol, 1.3 equiv) in CH_2Cl_2 (3 mL) *via* syringe. The mixture was stirred for 10 min at -78 ºC and then quenched with water (1 mL). The cold bath was removed, and the reaction mixture was allowed to warm to room temperature and then purged to a separatory funnel containing CH_2Cl_2 (10 mL) and water (10 mL). The aqueous layer was separated and extracted with CH_2Cl_2 (10 mL). The combined organic phases were washed with brine (20 mL), dried over $MgSO_4$, filtered, concentrated, and purified by column chromatography on silica gel (hexanes-EtOAc 1:1) to afford (-)-*anti*-**89a** (330 mg, 66%) as a yellow solid, and (-)-*syn*-**89a** (170 mg, 34%) as a yellow solid.

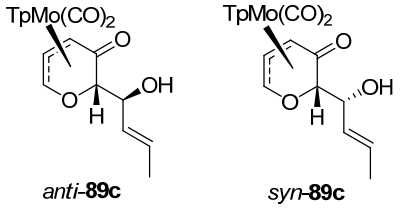
(-)-*anti*-**89a**: TLC (R_f = 0.39, hexanes-EtOAc 1:1). IR (cm^{-1}): 3401 (w), 3127 (w), 2980 (w), 2934 (w), 2899(w), 2486 (w), 1961 (s), 1872 (s), 1640 (m), 1505 (w), 1409 (m), 1305 (m), 1220 (m), 1123 (m), 1050 (m). ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.53 (d, *J* = 1.9 Hz, 1H), 7.91 (d, *J* = 1.9 Hz, 1H), 7.66 (d, *J* = 1.9 Hz, 1H), 7.63 (d, *J* = 2.2 Hz, 1H), 7.60 (d, *J* = 2.2 Hz, 1H), 7.53 (d, *J* = 2.2 Hz, 1H), 7.37 (dd, *J* = 1.9, 4.8 Hz, 1H), 6.33 (t, *J* = 2.2 Hz, 1H), 6.28 (t, *J* = 2.2 Hz, 1H), 6.23 (t, *J* = 2.2 Hz, 1H), 4.78 (dd, *J* = 2.2, 6.0 Hz, 1H), 4.21 (dd, *J* = 4.8, 6.4 Hz, 1H), 3.95 (m, 1H), 3.27 (d, *J* = 6.4 Hz, 1H), 3.08 (d, *J* = 4.8 Hz, 1H), 0.99 (d, *J* = 6.4 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 224.5, 223.6, 195.1, 147.7, 143.9, 141.8, 136.65, 136.62, 135.0, 107.5, 106.6, 106.4, 106.1, 79.0, 69.5, 68.8, 65.0, 18.7. Anal. Calcd for $C_{18}H_{19}BMoN_6O_5$: C, 42.72; H, 3.78; N, 16.60. Found: C, 42.32; H, 3.81; N, 16.17.

(-)-*anti*-**89a**: $[\alpha]_D^{20}$ = -357 (*c* = 0.105, CH_2Cl_2). HPLC: CHIRALPAK AS-RH column, CH_3CN : H_2O with 0.1% TFA = 35 : 65, 0.9 mL/min., λ = 254 nm, t_R = 21.65 min, 98.7% ee. Enantiomer: t_R = 14.78 min.

(-)-*syn*-**89a**: TLC (R_f = 0.31, hexanes-EtOAc 1:1). IR (cm^{-1}): 3405 (w), 3127 (w), 2976 (w), 2934 (w), 2490 (w), 1961 (s), 1872 (s), 1644 (m), 1505 (m), 1409 (m), 1305 (m), 1220 (m), 1123 (m), 1050 (m). ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.53 (d, *J* = 1.9 Hz, 1H), 7.91 (d, *J* = 2.2 Hz, 1H), 7.67 (d, *J* = 2.2 Hz, 1H), 7.63 (d, *J* = 1.9 Hz, 1H), 7.61 (d, *J* = 1.9 Hz, 1H), 7.53 (d, *J* = 1.9 Hz, 1H), 7.42 (dd, *J* = 2.22 Hz, *J* = 4.76 Hz, 1H), 6.33 (t, *J* = 2.2 Hz, 1H), 6.28 (t, *J* = 2.2 Hz, 1H), 6.23 (t, *J* = 2.2 Hz, 1H), 4.78 (dd, *J* = 2.2, 6.0 Hz, 1H), 4.20 (dd, *J* = 4.8, 6.4 Hz, 1H), 4.15 (m, 1H), 3.31 (d, *J* = 3.2 Hz, 1H), 2.39 (d, *J* =

8.9 Hz, 1H), 1.25 (d, J = 6.4 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): 224.7, 223.7, 195.0, 147.7, 144.0, 141.8, 136.63, 136.61, 135.0, 108.0, 106.6, 106.3 106.1, 78.9, 70.4, 68.8, 65.1, 19.2. Anal. Calcd for $C_{18}H_{19}BMoN_6O_5$: C, 42.72; H, 3.78; N, 16.60. Found: C, 43.01; H, 3.94; N, 16.34.

(-)-*syn*-**89a**: $[\alpha]_D^{20}$= -603 (c = 0.125, CH_2Cl_2). HPLC: CHIRALPAK AS-RH column, CH_3CN : H_2O = 40 : 60, 0.9 mL/min., λ = 254 nm, t_R = 14.41 min, 98.7% ee. Enantiomer: t_R = 11.77 min.



anti-**89c** *syn*-**89c**

(±)-Dicarbonyl[hydridotris(1-pyrazolyl)borato]{(2*S*,6*S*)-η-(2,3,4)-6-[(*S*,*E*)-1-hydroxylbuten-2-yl]-5-oxo-5,6-dihydro-2*H*-pyran-2-yl}molybdenum, (±)-*anti*-89c

and

(±)-Dicarbonyl[hydridotris(1-pyrazolyl)borato]{(2*S*,6*S*)-η-(2,3,4)-6-[(*R*,*E*)-1-hydroxylbuten-2-yl]-5-oxo-5,6-dihydro-2*H*-pyran-2-yl}molybdenum, (±)-*syn*-89c.

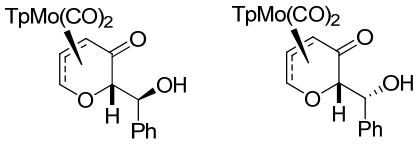
To a Schlenk flask charged with a solution of (±)-**86** (120 mg, 0.26 mmol, 1 equiv) in CH_2Cl_2 (5 mL) was successively added Et_3N (40 μL, 0.29 mmol, 1.1 equiv) and TBSOTf (63 μL, 0.3 mmol, 1.05 equiv). The reaction mixture was stirred for 30 min at room temperature, then cooled down to -78 ºC. To this mixture was slowly added a low-temperature (-78 ºC) premixed solution of crotonaldehyde (31 μL, 0.36 mmol, 1.4

equiv) and $TiCl_4$ (1.0 M in CH_2Cl_2, 0.34 mL, 0.34 mmol, 1.3 equiv) in CH_2Cl_2 (2 mL) *via* syringe. The mixture was stirred for 10 min at -78 ºC and then quenched with water (1 mL). The cold bath was removed, and the reaction mixture was allowed to warm to room temperature and then purged to a separatory funnel containing CH_2Cl_2 (10 mL) and water (30 mL). The combined organic layers were washed with water (2 × 10 mL) and brine (10 mL), dried over Na_2SO_4, filtered, concentrated, and purified by column chromatography on silica gel (hexanes-EtOAc 1:1) to afford (-)-*anti*-**89c**(37 mg, 27%) as a yellow solid, and (-)-*syn*-**89c**(19 mg, 14%) as a yellow solid.

(±)-*anti*-**89c**: TLC (R_f = 0.48, hexanes-EtOAc 1:1). IR (cm^{-1}): 3397 (m), 3127 (m), 2918 (w), 2887 (w), 2490 (m), 1961 (s), 1872 (s), 1644 (m), 1505 (m), 1409 (m), 1305 (m), 1220 (m), 1123 (m), 1050 (m). ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.52 (d, *J* = 1.9 Hz, 1H), 7.91 (d, *J* = 2.2 Hz, 1H), 7.66 (d, *J* = 1.9 Hz, 1H), 7.63 (d, *J*= 2.5 Hz, 1H), 7.61 (d, *J* = 2.2 Hz, 1H), 7.53 (d, *J* = 2.5 Hz, 1H), 7.40 (dd, *J* = 2.2, 4.8 Hz, 1H), 6.32 (t, *J* = 2.5 Hz, 1H), 6.27 (t, *J* = 2.2 Hz, 1H), 6.23 (t, *J* = 2.2 Hz, 1H), 5.80 (dqd, *J* = 15.3, 8.9, 1.0 Hz, 1H), 5.56 (ddq, *J* = 15.3, 7.3, 1.6 Hz, 1H), 4.79 (dd, *J* = 1.9, 6.0 Hz, 1H), 4.25 (m, 1H), 4.19 (dd, *J* = 4.8, 6.0 Hz, 1H), 3.42 (d, *J* = 5.4 Hz, 1H), 2.89 (d, *J* = 3.8 Hz, 1H), 1.75 (dd, *J* = 6.7, 1.3 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 224.6, 223.6, 194.2, 147.6, 143.9, 141.8, 136.60, 136.58, 135.0, 130.1, 128.5, 107.6, 106.6, 106.3, 106.0, 78.5, 73.8, 69.7, 65.1, 18.1. Anal. Calcd for $C_{20}H_{21}BMoN_6O_5$: C, 45.14; H, 3.98; N, 15.79. Found: C, 45.28; H, 4.12; N, 15.85.

(±)-*syn*-**89c**: TLC (R_f = 0.34, hexanes-EtOAc 1:1). IR (cm^{-1}): 3412 (m), 3127 (w),

2918 (w), 2887 (w), 2490 (m), 1961 (s), 1872 (s), 1644 (m), 1505 (m), 1409 (m), 1305 (m), 1220 (m), 1123 (m), 1050 (m). ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.52 (d, *J* = 1.9 Hz, 1H), 7.91 (d, *J* = 1.9 Hz, 1H), 7.66 (d, *J* = 2.2 Hz, 1H), 7.63 (d, *J* = 2.2 Hz, 1H), 7.60 (d, *J* = 1.9 Hz, 1H), 7.53 (d, *J* = 2.2 Hz, 1H), 7.41 (dd, *J* = 2.2, 4.8 Hz, 1H), 6.32 (t, *J* = 2.2 Hz, 1H), 6.27 (t, *J* = 2.5 Hz, 1H), 6.23 (t, *J* = 2.2 Hz, 1H), 5.80 (dqd, *J* = 15.3, 6.4, 1.3 Hz, 1H), 5.56 (ddq, *J* = 15.3, 6.4, 1.6 Hz, 1H), 4.83 (dd, *J* = 1.9, 6.4 Hz, 1H), 4.43 (m, 1H), 4.20 (dd, *J* = 4.8, 6.4 Hz, 1H), 3.41 (d, *J* = 3.2 Hz, 1H), 2.56 (d, *J* = 8.9 Hz, 1H), 1.74 (dt, *J* = 6.4, 1.3 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 224.7, 223.6, 194.5, 147.6, 144.0, 141.8, 136.62, 136.58, 135.0, 129.2, 129.0, 108.1, 106.6, 106.3, 106.1, 78.3, 73.2, 70.4, 65.0, 18.1. Anal. Calcd for $C_{20}H_{21}BMoN_6O_5$: C, 45.14; H, 3.98; N, 15.79. Found: C, 44.97; H, 4.01; N, 15.57.



anti-**89d** *syn*-**89d**

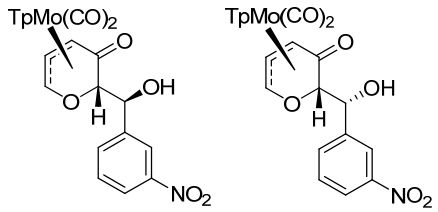
(±)-Dicarbonyl[hydridotris(1-pyrazolyl)borato]{(2*S*,6*S*)-*η*-(2,3,4)-6-[(*R*)-hydroxy-(phenyl)methyl]-5-oxo-5,6-dihydro-2*H*-pyran-2-yl}molybdenum, (±)-*anti*-89d and **(±)-Dicarbonyl[hydridotris(1-pyrazolyl)borato][(2*S*,6*S*)-*η*-(2,3,4)-6-((*S*)-hydroxy-(phenyl)methyl)-5-oxo-5,6-dihydro-2*H*-pyran-2-yl]molybdenum, (±)-*syn*-89d.**

To a Schlenk flask charged with a solution of (±)-**86** (462 mg, 1.00 mmol, 1 equiv) in CH_2Cl_2 (20 mL) was successively added Et_3N (0.15 mL, 1.10 mmol, 1.1 equiv) and

TBSOTf (0.25 mL, 1.10 mmol, 1.1 equiv). The reaction mixture was stirred for 30 min at room temperature, then cooled down to -78 ºC. To this mixture was slowly added a low temperature (-78 ºC) premixed solution of benzaldehyde (141 μL, 1.4 mmol, 1.4 equiv) and $TiCl_4$ (1.0 M in CH_2Cl_2, 1.3 mL, 1.30 mmol, 1.3 equiv) in CH_2Cl_2 (5 mL) *via* syringe. The mixture was stirred for 10 min at -78 ºC and then quenched with water (1 mL). The cold bath was removed, and the reaction mixture was allowed to warm to room temperature and then purged to a separatory funnel containing CH_2Cl_2 (20 mL) and water (30 mL). The combined organic layers were washed with water (2 × 10 mL) and brine (10 mL), dried over $MgSO_4$, filtered, concentrated, and purified by column chromatography on silica gel (hexanes-EtOAc-CH_2Cl_2 4:1:5) to afford (±)-*anti*-**89d** (460 mg, 81%) as a yellow solid, and (±)-*syn*-**89d** (51 mg, 9%) as a yellow solid.

(±)-*anti*-**89d**: TLC (R_f = 0.30, hexanes-EtOAc-CH_2Cl_2 2:1:4). IR (cm^{-1}): 3416 (br, m), 1965 (s), 1876 (s), 1637 (m), 1409 (w), 1305 (w), 1220 (w), 1123 (w), 1054 (m). ^1H NMR (400 MHz, $CDCl_3$): δ 8.50 (d, *J* = 2.0 Hz, 1 H), 7.85 (d, *J* = 2.0 Hz, 1 H), 7.58 (d, *J* = 2.0 Hz, 1 H), 7.57 (d, *J* = 2.0 Hz, 1 H), 7.50 (d, *J* = 2.0 Hz, 1 H), 7.37 (d, *J* = 2.0 Hz, 1 H), 7.38-7.28 (m, 5 H), 7.23 (dd, *J* = 2.0, 4.8 Hz, 1H), 6.29 (t, *J* = 2.4 Hz, 1 H), 6.21 (t, *J* = 2.4 Hz, 1 H), 6.19 (t, *J* = 2.4 Hz, 1 H), 4.86 (d, *J* = 6.4 Hz, 1 H), 4.63 (dd, *J* = 6.0, 1.6 Hz, 1 H), 3.88 (d, *J* = 4.8 Hz, 1 H), 3.65 (d, *J* = 6.0 Hz), 3.60 (br s, 1 H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 224.2, 223.4, 194.3, 147.7, 141.6, 138.9, 136.3, 134.7, 128.2, 127.4, 107.3, 106.4, 106.0, 105.8, 78.3, 74.5, 68.9, 64.7. HRMS (ESI) calcd for $C_{23}H_{22}BMoN_6O_5$ ($[M+H]^+$): 571.0793. Found: 571.0803.

(±)-*syn*-**89d**: TLC (R_f = 0.24, hexanes-EtOAc-CH_2Cl_2 2:1:4). IR (cm^{-1}): 3412 (br, m), 1961 (s), 1876 (s), 1640 (s), 1409 (s), 1305 (s), 1220 (s). ^1H NMR (400 MHz, $CDCl_3$): δ 8.50 (d, *J* = 2.0 Hz, 1 H), 7.85 (d, *J* = 2.0 Hz, 1 H), 7.59 (s, 1 H), 7.586 (s, 1 H), 7.57 (d, *J* = 2.0 Hz, 1 H), 7.37 (dd, *J* = 2.0, 0.4Hz, 1 H), 7.38-7.28 (m, 5 H), 7.29 (dd, *J* = 4.8, 2.4 Hz, 1H), 6.30 (t, *J* = 2.4 Hz, 1 H), 6.23 (t, *J* = 2.4 Hz, 1 H), 6.19 (t, *J* = 2.4 Hz, 1 H), 5.07 (d, *J* = 3.6 Hz, 1 H), 4.69 (dd, *J* = 6.0, 2.0 Hz, 1 H), 3.94 (dd, *J* = 6.0, 4.8 Hz, 1 H), 3.68 (d, *J* = 3.6 Hz, 1 H), 3.48 (br s, 1 H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 224.4, 223.4, 194.1, 147.4, 143.8, 141.6, 140.0, 136.3, 134.8, 128.2, 127.7, 126.5, 107.6, 106.3, 106.1, 105.8, 77.8, 73.7, 70.0, 64.9. HRMS (ESI) calcd for $C_{23}H_{22}BMoN_6O_5$ ($[M+H]^+$): 571.0793. Found: 571.0806.



anti-**89e** *syn*-**89e**

(±)-Dicarbonyl[hydridotris(1-pyrazolyl)borato]{(2*S*,6*S*)-η-(2,3,4)-6-[(*R*)-hydroxy (3-nitrophenyl)methyl]-5-oxo-5,6-dihydro-2*H*-pyran-2-yl}molybdenum, (±)-*anti*-89e

and

(±)-Dicarbonyl[hydridotris(1-pyrazolyl)borato]{(2*S*,6*S*)-η-(2,3,4)-6-[(*S*)-hydroxy (3-nitrophenyl)methyl]-5-oxo-5,6-dihydro-2*H*-pyran-2-yl}molybdenum, (±)-*syn*-89e.

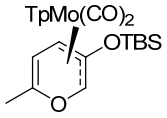
To a Schlenk flask charged with a solution of (±)-**86** (170 mg, 0.37 mmol, 1 equiv) in

CH_2Cl_2 (10 mL) was successively added Et_3N (56.4 μL, 0.41 mmol, 1.1 equiv) and TBSOTf (93 μL, 0.41 mmol, 1.1 equiv). The reaction mixture was stirred for 30 min at room temperature, then cooled down to -78 ºC. To this mixture was slowly added a low-temperature (-78 ºC) premixed solution of 3-nitrobenzaldehyde (110 mg, 0.74 mmol, 2 equiv) and $TiCl_4$ (1.0 M in CH_2Cl_2, 0.7 mL, 0.7 mmol, 1.9 equiv) in CH_2Cl_2 (1 mL) *via* syringe. The mixture was stirred for 10 min at -78 ºC and then quenched with water (1 mL). The cold bath was removed, and the reaction mixture was allowed to warm to room temperature and then purged to a separatory funnel containing CH_2Cl_2 (10 mL) and water (30 mL). The combined organic layers were washed with water (2 × 10 mL) and brine (10 mL), dried over Na_2SO_4, filtered, concentrated, and purified by column chromatography on silica gel (hexanes-EtOAc 1:1) to afford (±)-*anti*-**89e** (162 mg, 72%) as a yellow solid, and (±)-*syn*-**89e** (38 mg, 17%) as a yellow solid.

(±)-*anti*-**89e**: TLC (R_f = 0.44 hexanes-EtOAc 1:1). IR (cm^{-1}): 3393 (br w), 2490 (w), 1956 (s), 1880 (s), 1633 (s), 1529 (s), 1409 (s), 1351(s), 1285 (s). ^1H NMR (600 MHz, $CDCl_3$): δ 8.49 (d, *J* = 2.4 Hz, 1 H), 8.28 (s, 1 H), 8.18 (dt, *J* = 7.2, 1.2 Hz, 1 H), 7. 86 (d, *J* = 1.8 Hz, 1 H), 7.74 (d, *J* = 7.2 Hz, 1 H), 7.60 (dd, *J* = 4.8, 2.4 Hz, 2 H), 7.57 (d, *J* = 1.8 Hz, 1 H), 7.55 (t, *J* = 8.1 Hz, 1 H), 7.51 (d, *J* = 2.4 Hz, 1 H), 7.20 (dd, *J* = 4.8, 1.8 Hz, 1 H), 6.31 (t, *J* = 2.1 Hz, 1 H), 6.24 (t, *J* = 2.1 Hz, 1 H), 6.22 (t, *J* = 2.4 Hz, 1 H), 4.88 (dd, *J* = 7.2, 2.4 Hz, 1 H), 4.73 (dd, *J* = 6.6, 2.4 Hz, 1 H), 4.19 (d, *J* = 2.4 Hz, 1 H), 4.07 (dd, *J* = 5.4, 4.8 Hz, 1 H), 3.48 (d, *J* = 7.2 Hz, 1 H). ^{13}C NMR (150 MHz, $CDCl_3$): δ 223.5, 223.0, 194.1, 148.0, 147.4, 143.8, 141.6, 141.5, 136.5 (2C), 134.8, 133.4, 129.1, 123.1,

122.7, 106.5, 106.2, 105.9 (2C), 77.4, 73.4, 69.4, 64.9. HRMS (ESI) calcd for $C_{23}H_{21}BMoN_7O_7$ ($[M+H]^+$): 616.0644. Found: 616.0655.

(±)-*syn*-**89e**: TLC (R_f = 0.29 hexanes-EtOAc 1:1). IR (cm^{-1}): 3393 (br w), 2926 (w), 2490 (w), 1956 (s), 1876 (s), 1633 (m), 1529 (s), 1409 (s), 1351(s), 1305 (s). ^1H NMR (600 MHz, $CDCl_3$): δ 8.50 (d, *J* = 1.8 Hz, 1 H), 8.31 (s, 1 H), 8.16 (dd, *J* = 8.4, 1.2 Hz, 1 H), 7. 83 (d, *J* = 1.8 Hz, 1 H), 7.72 (d, *J* = 7.2 Hz, 1 H), 7.60 (m, 2 H), 7.58 (d, *J* = 2.4 Hz, 1 H), 7.54 (t, *J* = 7.8 Hz, 1 H), 7.51 (d, *J* = 1.8 Hz, 1 H), 7.27 (dd, *J* = 4.5, 2.1 Hz, 1 H), 6.31 (t, *J* = 2.1 Hz, 1 H), 6.24 (t, *J* = 2.4 Hz, 1 H), 6.20 (t, *J* = 2.4 Hz, 1 H), 5.16 (br s, 1 H), 4.67 (dd, *J* = 6.0, 1.8 Hz, 1 H), 4.00 (dd, *J* = 6.0, 4.8 Hz, 1 H), 3.82 (br d, *J* = 6.6, 6.6 Hz, 1 H), 3.67 (d, *J* = 3.6 Hz, 1 H). ^{13}C NMR (150 MHz, $CDCl_3$): δ 223.9, 223.0, 193.3, 148.1, 147.4, 143.8, 142.1, 141.5, 136.5 (2C), 134.8, 132.5, 129.1, 122.8, 121.8, 106.5, 106.3, 106.2, 105.9, 77.2, 72.8, 70.3, 64.9. HRMS (ESI) calcd for $C_{23}H_{21}BMoN_7O_7$ ($[M+H]^+$): 616.0644. Found: 616.0646.



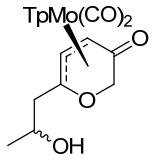
90

(±)-Dicarbonyl[hydridotris(1-pyrazolyl)borato][(2*R*)-η-(2,3,4)-3-(*tert*-butyldimethylsilyloxy)-6-methyl--3,4-dihydro-2*H*-pyran-2-yl]molybdenum, (±)-90.

To a Schlenk flask charged with a solution of (±)-**88** (500 mg, 1.05 mmol, 1 equiv) in CH_2Cl_2 (10 mL) at room temperature was successively added Et_3N (0.16 mL, 1.16 mmol, 1.1 equiv) and TBSOTf (0.27 mL, 1.16 mmol, 1.1 equiv). The reaction mixture turned

from purple suspension to brownish yellow solution. After being stirred for 3 hr, the solution was directly passed through a short silica gel column. The solvents were completely removed on a rotary evaporator, and the residue was further purified by column chromatography on silica gel (hexanes-EtOAc 2:1) to afford **90** (573 mg, 92%) as a brown solid.

(±)-**90**: TLC (R_f = 0.78, hexanes-EtOAc 1:2). IR (cm^{-1}): 2957 (w), 2930 (m), 2474 (w), 1938 (s), 1853 (s), 1656 (w), 1505 (m), 1463 (m), 1409 (m). ^{1}H NMR (400 Hz, acetone-d_6): δ 8.45 (br s, 1H), 8.14 (br s, 1H), 8.10 (d, *J* = 1.6 Hz, 1H), 7.84 (br s, 1H), 7.74 (d, *J* = 1.6 Hz, 1H), 7.70 (br s, 3H), 7.68 (d, *J* = 2.4 Hz, 1H), 6.29 (t, *J* = 2.2 Hz, 1H), 6.25 (d, *J* = 2.2 Hz, 1H), 6.22 (br s, 1H), 5.85 (br s, 1H), 5.16 (br s, 1H), 2.84 (br s, 1H), 1.74 (br s, 3H), 0.43 (br s, 9H), 0.05 (br s, 3H), 0.04 (br s, 3H). ^{13}C NMR (100 Hz, $CDCl_3$): 229.5, 223.1, 145.4, 143.1, 142.4, 141.7, 135.6, 135.0, 134.2, 105.9, 105.1, 105.0, 104.5, 104.1, 91.0, 60.9, 24.9, 17.8, 17.4, -4.92. HRMS (ESI) Calcd for $C_{23}H_{31}BMoN_6O_4Si$ ([M]$^+$): 592.1318. Found: 592.1331.



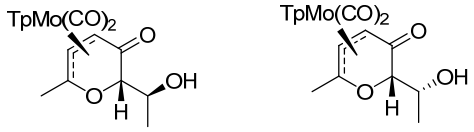
91

(±)-Dicarbonyl[hydridotris(1-pyrazolyl)borato][(2*S*,6*S*)-*η*-(2,3,4)-2-(2-hydroxylpropyl)-5-oxo-5,6-dihydro-2*H*-pyran-2-yl]molybdenum, (±)-91.

To a Schlenk flask charged with a solution of (±)-**88** (95 mg, 0.20 mmol, 1 equiv) in CH_2Cl_2 (5 mL) at -78 ºC was successively added Et_3N (31 μL, 0.22 mmol, 1.1 equiv) and TBSOTf (51 μL, 0.22 mmol, 1.1 equiv). The reaction mixture was slowly warmed to -40 ºC over 15 min and stirred for 10 min at -40 ºC. The reaction mixture was cooled down to -78 ºC. To this mixture was slowly added a low-temperature (-78 ºC) premixed solution of acetaldehyde (34 μL, 0.60 mmol, 3 equiv) and $TiCl_4$ (1.0 M in CH_2Cl_2, 0.54 mL, 0.54 mmol, 2.7 equiv) in CH_2Cl_2 (2 mL) *via* syringe. The mixture was stirred for 10 min at -78 ºC and then quenched with water (1 mL). The cold bath was removed, and the reaction mixture was allowed to warm to room temperature and then purged to a separatory funnel containing CH_2Cl_2 (10 mL) and water (10 mL). The combined organic layers were washed with water (2 × 10 mL) and brine (10 mL), dried over $MgSO_4$, filtered, concentrated, and purified by column chromatography on silica gel (hexanes-EtOAc 2:1) to afford brownish pink solid (±)-**91** (72 mg, 69%) as a inseparable mixture of two stereomers (10 : 1, determined by ^{1}H NMR).

(±)-**91** (major isomer): TLC (R_f = 0.36, hexanes-EtOAc 1:2). IR (cm^{-1}): 3389 (br w), 2486 (w), 1934 (s), 1841 (s), 1625 (s), 1509 (m), 1409 (s), 1309 (s). ^{1}H NMR (400 Hz, $CDCl_3$): δ 8.46 (br s, 1H), 8.30 (br s, 1H), 7.68 (br s, 1H), 7.58 (br s, 3H), 6.23 (br s, 3H), 4.96 (d, *J* = 6.0 Hz, 1H), 4.73 (d, *J* = 6.4 Hz, 1H), 4.36 (m, 1H), 3.74 (s, 2H), 3.05 (dd, *J* = 14.4, 6.0 Hz, 1H), 2.97 (dd, *J* = 14.4, 4.8 Hz, 1H), 1.39 (d, *J* = 6.4 Hz, 1H). ^{13}C NMR (100 Hz, $CDCl_3$): δ 240.0, 227.0, 190.3, 147.5 (br), 144.62 (br), 144.6, 142.9 (br), 136.1 (br), 135.6 (br), 134.8 (br), 105.9(3C), 74.0, 68.3, 67.7, 67.3, 46.4, 22.9. HRMS (ESI)

Calcd for $C_{19}H_{22}BMoN_6O_5$ ([M+H]$^+$): 523.0793. Found: 523.0811.



(±)-*anti*-**89f** (±)-*syn*-**89f**

(±)-Dicarbonyl[hydridotris(1-pyrazolyl)borato]{(2*S*,6*S*)-η-(2,3,4)-6-[(*S*)-1-hydroxyethyl]-2-methyl-5-oxo-5,6-dihydro-2*H*-pyran-2-yl}molybdenum, (±)-*anti*-89f and

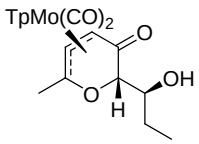
(±)-Dicarbonyl[hydridotris(1-pyrazolyl)borato]{(2*S*,6*S*)-η-(2,3,4)-6-[(*R*)-1-hydroxyethyl)-2-methyl-5-oxo-5,6-dihydro-2*H*-pyran-2-yl}molybdenum, (±)-*syn*-89f.

To a solution of (±)-**88** (137 g, 0.29 mmol, 1 equiv) in dry CH_2Cl_2 (5 mL) was added LiHMDS (1.0 M in THF, 0.58 mL, 0.58 mmol, 4 equiv) at -78 ºC. The reaction mixture was stirred at -78 ºC for 30 min followed by addition of acetaldehyde (65 μL, 1.16 mmol, 4 equiv). After being stirred for 15 min at -78 ºC, the reaction was quenched with saturated NH_4Cl (1 mL). Then the cold solution was purged to a separatory funnel and washed with H_2O (10 mL) and CH_2Cl_2 (10 mL). The organic layers were collected and washed with brine (10 mL), dried over $MgSO_4$, filtered, concentrated, and purified by column chromatography on silica gel (CH_2Cl_2-EtOAc-hexanes 4:2:1) to afford (±)-*anti*-**89f** (59 mg, 39%) as a brown solid, and (±)-*syn*-**89f** (32 mg, 22%) as a brown solid.

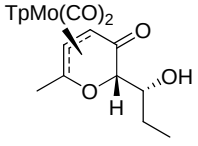
(±)-*anti*-**89f**: TLC (R_f = 0.27, CH_2Cl_2-EtOAc-hexanes 4:2:1). IR (cm^{-1}): 3420 (br m),

2976 (w), 2930 (w), 2490 (m), 1930 (s), 1841 (s), 1629 (s), 1521 (s), 1409 (s), 1305(s), 1220 (s). ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.48 (br s, 1H), 8.29 (br s, 1H), 7.60 (br, 4H), 6.25 (br s, 3H), 4.89 (d, *J* = 6.0 Hz, 1H), 4.53 (d, *J* = 6.0 Hz, 1H), 3.94 (m, 1H), 3.59 (d, *J* = 6.0 Hz, 1H), 2.98 (d, *J* = 4.0 Hz, 1H), 2.64 (s, 3H), 1.22 (d, *J* = 6.4 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 239.6, 227.5, 191.2, 147.7(br), 144.7(br), 144.5, 142.4(br), 136.2(br), 135.5(br), 134.5(br), 106.0(br 3C), 81.5, 72.5, 68.7, 67.1, 24.2, 18.7. HRMS (ESI) Calcd for $C_{19}H_{22}BMoN_6O_5$ ($[M+H]^+$) : 523.0793. Found: 523.0793.

(±)-*syn*-**89f**: TLC (R_f = 0.21 CH_2Cl_2-EtOAc-hexanes 4:2:1). IR (cm^{-1}): 3397 (br w), 2926 (w), 2486 (w), 1930 (s), 1837 (s), 1621 (s), 1525 (m), 1409 (m), 1305(m), 1220 (m). ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.44 (br s, 1H), 8.27 (br s, 1H), 7.56 (br, 4H), 6.22 (br s, 3H), 4.91 (d, *J* = 6.4 Hz, 1H), 4.50 (d, *J* = 6.0 Hz, 1H), 4.20 (qd, *J* = 6.8, 2.8 Hz, 1H), 3.62 (d, *J* = 2.8 Hz, 1H), 2.61 (s, 3H), 1.20 (d, *J* = 6.4 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 239.8, 228.0, 192.0, 147.7(br), 147.3, 144.6(br), 142.5(br), 136.2(br), 135.6(br), 134.7(br), 106.0(br 3C), 81.4, 72.3, 68.7, 67.6, 24.3, 19.0. HRMS (ESI) Calcd for $C_{19}H_{22}BMoN_6O_5$ ($[M+H]^+$): 523.0793. Found: 523.0797.



(±)-*anti*-**89g**



(±)-*syn*-**89g**

(±)-Dicarbonyl[hydridotris(1-pyrazolyl)borato]{(2*S*,6*S*)-*η*-(2,3,4)-6-[(*S*)-1-hydroxypropyl]-2-methyl-5-oxo-5,6-dihydro-2*H*-pyran-2-yl}molybdenum,

(±)-*anti*-89g and

(±)-Dicarbonyl[hydridotris(1-pyrazolyl)borato]{(2*S*,6*S*)-η-(2,3,4)-6-[(*R*)-1-hydroxypropyl]-2-methyl-5-oxo-5,6-dihydro-2*H*-pyran-2-yl}molybdenum, (±)-*syn*-89g.

To a solution of (±)-**88** (2.7 g, 5.67 mmol, 1 equiv) in dry CH_2Cl_2 (100 mL) was added LiHMDS (1.0 M in THF, 11. 34 mL, 11.34 mmol) at -78 ºC. The reaction mixture was stirred at -78 ºC for 30 min followed by addition of propaldehyde (1.64 mL, 22.68 mmol, 4 equiv). After being stirred for 15 min at -78 ºC, the reaction was quenched with saturated NH_4Cl (5 mL). Then the solution was immediately washed with H_2O (2 x 50 mL) and brine (50 mL). The combined organic layers were dried over $MgSO_4$, filtered, concentrated, and purified by column chromatography on silica gel (CH_2Cl_2-EtOAc-hexanes 4:2:1) to afford (±)-*anti*-**89g** (1.9 g, 63%) as a brown solid, and (±)-*syn*-**89g** (0.5 g, 17%) as a brown solid.

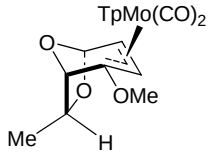
(±)-*anti*-**89g**: TLC (R_f = 0.60, CH_2Cl_2-EtOAc-hexanes 4:2:1). IR (cm^{-1}): 3424 (br m), 2926 (m), 2486 (s),1934 (s), 1841 (s), 1629 (s), 1521 (s), 1409 (s), 1305(s), 1220 (s). ^1H NMR (400 MHz, $CDCl_3$): δ 8.48 (br s, 1H), 8.30 (br s, 1H), 7.60 (br, 4H), 6.24 (br s, 3H), 4.89 (d, *J* = 6.0 Hz, 1H), 4.53 (d, *J* = 6.0 Hz, 1H), 3.70 (m, 1H), 3.65 (d, *J* = 6.0 Hz, 1H), 2.95 (d, *J* = 4.4 Hz, 1H), 2.62 (s, 3H), 1.68 (m, 1H), 1.45 (m, 1H), 0.99 (t, *J* = 8.4 Hz, 3H). ^{13}C NMR (150 MHz, $CDCl_3$): δ 239.6, 227.6, 191.6, 147.7, 144.8, 144.7, 142.4, 136.4, 135.5, 134.5, 106.1(3C), 80.5, 73.6, 72.5, 67.2, 25.6, 24.3, 9.6. HRMS (ESI) Calcd for $C_{20}H_{24}BMoN_6O_5$ ($[M+H]^+$): 537.0950. Found: 537.0943.

(±)-*syn*-**89g**: TLC (R_f = 0.40, CH_2Cl_2-EtOAc-hexanes 4:2:1). IR (cm^{-1}): 3362 (m), 2922

(m), 2486 (m), 1922 (s), 1830 (s), 1633 (s), 1505 (s), 1409 (s), 1305(s), 1216 (s). ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.46 (br s, 1H), 8.28 (br s, 1H), 7.60 (br, 4H), 6.24 (br s, 3H), 4.92 (d, J = 6.0 Hz, 1H), 4.48 (d, J = 6.0 Hz, 1H), 3.95 (m, 1H), 3.70 (d, J = 2.4 Hz, 1H), 2.61 (s, 3H), 2.95 (br s, 1H), 1.52 (m, 2H), 0.98 (t, J = 7.6 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 239.6, 228.2, 192.3, 148.2, 147.6, 144.5, 142.4, 136.2, 135.5, 134.6, 105.9 (3C), 80.6, 74.2, 72.0, 67.5, 26.0, 24.3, 10.3. HRMS (ESI) Calcd for $C_{20}H_{24}BMoN_6O_5$ ($[M+H]^+$): 537.0950. Found: 537.0946.

General procedure for the intramolecular '1,5-Michael-like' reaction.

To a Schlenk flask charged with molybdenum complex *syn*-**89** or *anti*-**89** (1 equiv) in dry THF was added NaH (60% dispersed in mineral oil, 2 equiv) under argon. After being stirred for 2 to 6 h at room temperature, the reaction was cooled to 0 ºC. To the reaction mixture was added solid Me_3OBF_4 (2 equiv). *More Me_3OBF_4 may be needed to complete the reaction, which highly depends on the quality of the Me_3OBF_4.* Then the reaction was stirred at 0 ºC for indicated time after which TLC showed the formation of a new compound. The reaction was quenched by adding Et_3N at 0 ºC. The cold solution was directly passed through a short silica gel column (pre-neutralized by 5% Et_3N) with Et_2O. The solvents were completely removed on a rotary evaporator, and the residue was further purified by flash chromatography on silica gel neutralized with 5% Et_3N.

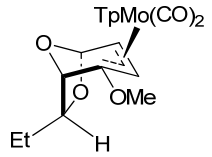


94a

(±)-Dicarbonyl[hydridotris(1-pyrazolyl)borato][(1*S*,2*S*,5*S*,7*R*)-η-(2,3,4)-2-methoxy-7-methyl-6,8-dioxabicyclo[3.2.1]oct-3-en-2-yl]molybdenum, (±)-94a.

Following the general procedure, to a THF (3 mL) solution of the molybdenum complex *syn*-**89a** (43 mg, 0.085 mmol, 1 equiv) was added NaH (6.8 mg, 0.17 mmol, 2 equiv). The reaction mixture was stirred at room temperature for 30 min, then cooled to 0 ^{o}C followed by addition of solid Me_3OBF_4 (25 mg, 0.17 mmol, 2 equiv). The resulting mixture was stirred for 40 min at 0 ^{o}C, and quenched with Et_3N (1 mL). After work up, the crude product was purified by flash chromatography on silica gel eluting with hexanes-EtOAc (2 : 1) to afford **94a** (41 mg, 93%) as a yellow solid.

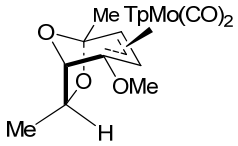
(±)-**94a**: TLC (R_f = 0.64, hexanes-EtOAc 1:1). IR (cm^{-1}): 2980 (m), 2930 (m), 2482 (m), 1930 (s), 1841 (s), 1505 (s), 1409 (s), 1305 (s), 1212 (s). ^{1}H NMR (600 MHz, $CDCl_3$): δ 8.44 (d, *J* = 1.2 Hz, 1H), 7.95 (d, *J* = 1.8 Hz, 1H), 7.61 (s, 2H), 7.57 (d, *J* = 1.2 Hz, 1H), 7.49 (d, *J* = 1.8 Hz, 1H), 6.24 (t, *J* = 2.1 Hz, 1H), 6.20 (t, *J* = 1.8 Hz, 1H), 6.16 (t, *J* = 2.1 Hz, 1H), 5.51 (d, *J* = 2.8 Hz, 1H), 4.28 (q, *J* = 6.2 Hz, 1H), 4.12 (d, *J* = 1.2 Hz, 1H), 3.83 (dd, *J* = 7.2, 3.0 Hz, 1H), 3.66 (d, *J* = 7.2 Hz, 1H), 3.25 (s, 3H), 1.26 (d, *J* = 6.0 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 230.0, 227.7, 146.2, 144.6, 140.1, 136.4, 135.8, 134.3, 131.6, 105.6, 105.45, 105.39, 102.9, 78.5, 78.2, 57.1, 51.6, 54.7, 21.1. HRMS (ESI) Calcd for $C_{19}H_{22}BMoN_6O_5$ ($[M+H]^+$): 523.0790. Found: 523.0793.



(±)-Dicarbonyl[hydridotris(1-pyrazolyl)borato][(1*S*,2*S*,5*S*,7*R*)-η-(2,3,4)-7-ethyl-2-methoxy-6,8-dioxabicyclo[3.2.1]oct-3-en-2-yl]molybdenum, (±)-94b.

Following the general procedure, to a THF (5 mL) solution of the molybdenum complex *syn*-**89b** (52 mg, 0.10 mmol, 1 equiv) was added NaH (8 mg, 0.20 mmol, 2 equiv). The reaction mixture was stirred at room temperature for 1 h, then cooled to 0 ^{o}C followed by addition of solid Me_3OBF_4 (30 mg, 0.20 mmol, 2 equiv). The resulting mixture was stirred for 1 h at 0 ^{o}C, and quenched with Et_3N (1 mL). After work up, the crude product was purified by flash chromatography on silica gel eluting with hexanes/EtOAc (2 : 1) to afford **94b** (52 mg, 97%) as a yellow solid.

(±)-**94b**: TLC (R_f = 0.70, hexanes-EtOAc 2:1). IR (cm^{-1}): 2972 (w), 2482 (w), 1930 (s), 1841 (s), 1505 (m), 1409 (s), 1305 (s), 1212 (s). ^{1}H NMR (600 MHz, $CDCl_3$): δ 8.45 (d, *J* = 1.2 Hz, 1H), 7.96 (d, *J* = 1.2 Hz, 1H), 7.61 (t, *J* = 1.8 Hz, 2H), 7.57 (d, *J* = 1.2 Hz, 1H), 7.49 (d, *J* = 1.6 Hz, 1H), 6.24 (t, *J* = 1.4 Hz, 1H), 6.20 (t, *J* = 1.6 Hz, 1H), 6.16 (t, *J* = 1.6 Hz, 1H), 5.50 (dd, *J* = 1.6, 0.4 Hz, 1H), 4.19 (d, *J* = 1.2 Hz, 1H), 4.02 (t, *J* = 4.4 Hz, 1H), 3.84 (dd, *J* = 5.2, 1.6 Hz, 1H), 3.68 (d, *J* = 5.2 Hz, 1H), 3.27 (s, 3H), 1.62-1.47 (m, 2H), 0.97 (d, *J* = 5.0 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 229.7, 227.5, 146.2, 144.6, 140.2, 136.4, 135.8, 134.3, 131.6,105.6, 105.45, 105.38, 102.8, 83.8, 76.8, 57.2, 56.6, 54.8, 27.8, 10.0. HRMS (ESI) Calcd for $C_{20}H_{24}BMoN_6O_5$ ($[M+H]^+$): 537.0950. Found: 537.0949.

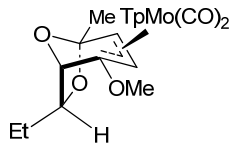


94c

(±)-Dicarbonyl[hydridotris(1-pyrazolyl)borato][(1*S*,2*S*,5*S*,7*R*)-η-(2,3,4)-5,7-dimethyl-2-methoxy-6,8-dioxabicyclo[3.2.1]oct-3-en-2-yl]molybdenum, (±)-94c.

Following the general procedure, to a THF (3 mL) solution of the molybdenum complex *syn*-**89f** (20 mg, 0.038 mmol, 1 equiv) was added NaH (3 mg, 0.075 mmol, 2 equiv). The reaction mixture was stirred at room temperature for 1 h, then cooled to 0 ^{o}C followed by addition of solid Me_3OBF_4 (11.3 mg, 0.076 mmol, 2 equiv). The resulting mixture was stirred for 1 h at 0 ^{o}C, and quenched with Et_3N (1 mL). After work up, the crude product was purified by flash chromatography on silica gel eluting with hexanes/EtOAc (2 : 1) to afford **94c** (20.2 mg, 99%) as a yellow solid.

(±)-**94c**: TLC (R_f = 0.66, hexanes-EtOAc 2:1). IR (cm^{-1}): 2980 (w), 2945 (w), 2463 (w), 1934 (s), 1841 (s), 1505 (m), 1409 (s), 1305 (s), 1216 (s). ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.50 (d, *J* = 1.6 Hz, 1H), 8.05 (d, *J* = 1.6 Hz, 1H), 7.63 (d, *J* = 1.6 Hz, 1H), 7.60 (d, *J* = 2.0 Hz, 2H), 7.50 (d, *J* = 2.0 Hz, 1H), 6.26 (t, *J* = 2.2 Hz, 1H), 6.20 (t, *J* = 2.2 Hz, 1H), 6.15 (t, *J* = 2.2 Hz, 1H), 4.23 (q, *J* = 6.4 Hz, 1H), 4.20 (d, *J* = 1.6 Hz, 1H), 3.90 (d, *J* = 7.6 Hz, 1H), 3.73 (dd, *J* = 8.2, 1.8 Hz, 1H), 3.34 (s, 3H), 1.73 (s, 3H), 1.25 (d, *J* = 6.4 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 231.7, 228.0, 146.2, 144.7, 141.2, 136.4, 135.8, 134.3, 126.1, 108.6, 105.7, 105.42, 105.37, 80.0, 77.1, 64.9, 57.0, 56.4, 23.0, 12.3. HRMS (ESI) Calcd for $C_{20}H_{24}BMoN_6O_5$ ($[M+H]^+$): 537.0950. Found: 537.0946.



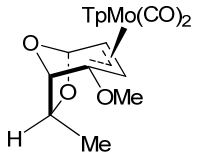
94d

(±)-Dicarbonyl[hydridotris(1-pyrazolyl)borato][(1*S*,2*S*,5*S*,7*R*)-η-(2,3,4)-7-ethyl-5-methyl-2-methoxy-6,8-dioxabicyclo[3.2.1]oct-3-en-2-yl]molybdenum, (±)-94d.

Following the general procedure, to a THF (8 mL) solution of the molybdenum complex *syn*-**89g** (32 mg, 0.06 mmol, 1 equiv) was added NaH (4.8 mg, 0.12 mmol, 2 equiv). The reaction mixture was stirred at room temperature for 1 h, then cooled to 0 ^{o}C followed by addition of solid Me_3OBF_4 (17.7 mg, 0.12 mmol, 2 equiv). The resulting mixture was stirred for 40 min at 0 ^{o}C, and quenched with Et_3N (1 mL). After work up, the crude product was purified by flash chromatography on silica gel eluting with hexanes-EtOAc (2 : 1) to afford **94d** (32 mg, 98%) as a yellow solid.

(±)-**94d**: TLC (R_f = 0.62, hexanes-EtOAc 2:1). IR (cm^{-1}): 2964 (m), 2937 (m), 2482 (m), 1938 (s), 1849 (s), 1505 (m), 1423 (s), 1409 (s), 1305 (s), 1216 (s). ^{1}H NMR (600 MHz, $CDCl_3$): δ 8.50 (d, *J* = 1.8 Hz, 1H), 8.07 (d, *J* = 2.4 Hz, 1H), 7.63 (d, *J* = 1.8 Hz, 1H), 7.60 (d, *J* = 2.4 Hz, 2H), 7.50 (d, *J* = 2.4 Hz, 1H), 6.26 (t, *J* = 2.1 Hz, 1H), 6.20 (t, *J* = 2.1 Hz, 1H), 6.15 (t, *J* = 2.1 Hz, 1H), 4.28 (d, *J* = 2.4 Hz, 1H), 3.97 (t, *J* = 6.6 Hz, 1H), 3.91 (d, *J* = 7.8 Hz, 1H), 3.75 (dd, *J* = 7.8, 1.8 Hz, 1H), 3.38 (s, 3H), 1.72 (s, 3H), 1.62-1.48 (m, 2H), 0.96 (t, *J* = 7.2 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 231.7, 228.5, 146.5, 145.0, 141.5, 136.6, 136.1, 134.5, 126.3, 108.6, 105.9, 105.7, 105.6, 83.0, 73.4, 65.6, 57.5, 56.5, 28.3, 23.0, 10.2. HRMS (ESI) Calcd for $C_{21}H_{26}BMoN_6O_5$ ($[M+H]^+$):

551.1106. Found: 551.1104.



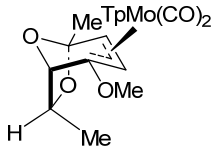
95a

(±)-Dicarbonyl[hydridotris(1-pyrazolyl)borato][(1*S*,2*S*,5*S*,7*S*)-η-(2,3,4)-2-methoxy-7-methyl-6,8-dioxabicyclo[3.2.1]oct-3-en-2-yl]molybdenum, (±)-95a.

Following the general procedure, to a THF (1.5 mL) solution of the molybdenum complex *anti*-**89a** (54 mg, 0.107 mmol, 1 equiv) was added NaH (8.5 mg, 0.21 mmol, 2 equiv). The reaction mixture was stirred at room temperature for 4.5 h, then cooled to 0 ^{o}C followed by addition of solid Me_3OBF_4 (31.5 mg, 0.21 mmol, 2 equiv). The resulting mixture was stirred for 40 min at 0 ^{o}C, and quenched with Et_3N (1 mL). After work up, the crude product was purified by flash chromatography on silica gel eluting with hexanes-EtOAc (2 : 1) to afford **95a** (44 mg, 93%) as a yellow solid.

(±)-**95a**: TLC (R_f = 0.62, hexanes-EtOAc 1:1). IR (cm^{-1}): 2984 (w), 2934 (w), 2482 (m), 1926 (s), 1841 (s), 1505 (s), 1409 (s), 1305(s), 1212 (s). ^{1}H NMR (600 MHz, $CDCl_3$): δ 8.41 (d, *J* = 1.8 Hz, 1H), 7.90 (d, *J* = 1.8 Hz, 1H), 7.63 (d, *J* = 2.4 Hz, 1H), 7.62 (d, *J* = 1.8 Hz, 1H), 7.57 (d, *J* = 2.4 Hz, 1H), 7.49 (d, *J* = 2.4 Hz, 1H), 6.23 (t, *J* = 2.1 Hz, 1H), 6.22 (t, *J* = 2.4 Hz, 1H), 6.176 (t, *J* = 2.4 Hz, 1H), 5.38 (d, *J* = 1.8 Hz, 1H), 4.44 (dd, *J* = 3.9, 1.5 Hz, 1H), 4.22 (qd, *J* = 6.6, 3.6 Hz, 1H), 3.87 (dd, *J* = 7.8, 2.4 Hz, 1H), 3.75 (d, *J* = 7.8 Hz, 1H), 3.12 (s, 3H), 1.49 (d, *J* = 6.0 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$):

δ 230.7, 228.4, 146.2, 144.8, 140.1, 136.4, 135.8, 134.3, 132.0, 105.6, 105.50, 105.47, 102.5, 76.8, 76.3, 57.2, 56.3, 54.4, 15.0. HRMS (ESI) Calcd for $C_{19}H_{22}BMoN_6O_5$ ($[M+H]^+$): 523.0793. Found: 523.0793.



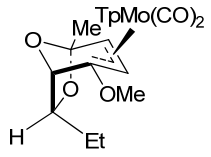
95b

(±)-Dicarbonyl[hydridotris(1-pyrazolyl)borato][(1*S*,2*S*,5*S*,7*S*)-η-(2,3,4)-5,7-dimethyl-2-methoxy-6,8-dioxabicyclo[3.2.1]oct-3-en-2-yl]molybdenum, (±)-95b.

Following the general procedure, to a THF (5 mL)solution of the molybdenum complex *anti*-**89f** (50 mg, 0.096 mmol, 1 equiv) was added NaH (7.7 mg, 0.19 mmol, 2 equiv). The reaction mixture was stirred at room temperature for 4 h, then cooled to 0 ^oC followed by addition of solid Me_3OBF_4 (28.4 mg, 0.19 mmol, 2 equiv). The resulting mixture was stirred for 40 min at 0 ^oC, and quenched with Et_3N (1 mL). After work up, the crude product was purified by flash chromatography on silica gel eluting with hexanes-EtOAc (2 : 1) to afford **95b** (39 mg, 76%) as a yellow solid.

(±)-**95b**: TLC (R_f = 0.41, hexanes-EtOAc 2:1). IR (cm^{-1}): 2991 (m), 2941 (w), 2482 (m), 1934 (s), 1841 (s), 1505 (s), 1409 (s), 1305 (s), 1216 (s). ^1H NMR (400 MHz, $CDCl_3$): δ 8.47 (d, *J* = 1.6 Hz, 1H), 8.00 (d, *J* = 1.6 Hz, 1H), 7.61 (m, 3H), 7.49 (d, *J* = 2.4 Hz, 2H), 6.25 (t, *J* = 2.2 Hz, 1H), 6.21 (t, *J* = 2.2 Hz, 1H), 6.16 (t, *J* = 2.2 Hz, 1H), 4.54 (dd, *J* = 3.6, 1.6 Hz, 1H), 4.26 (m, 1H), 3.96 (d, *J* = 8.0 Hz, 1H), 3.82 (dd, *J* = 8.0,

1.6 Hz, 1H), 3.22 (s, 3H), 1.69 (s, 3H), 1.45 (d, J = 6.4 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 232.7, 229.1, 146.1, 144.9, 141.1, 136.4, 135.8, 134.3, 126.3, 108.1, 105.6, 105.5, 105.4, 78.3, 75.5, 64.9, 58.8, 54.4, 22.5, 15.0. HRMS (ESI) Calcd for $C_{20}H_{24}BMoN_6O_5$ ($[M+H]^+$): 537.0950. Found: 537.0946



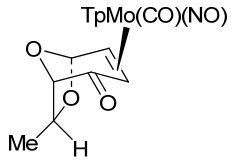
95c

(±)-Dicarbonyl[hydridotris(1-pyrazolyl)borato][(1*S*,2*S*,5*S*,7*S*)-η-(2,3,4)-7-ethyl-5-methyl-2-methoxy-6,8-dioxabicyclo[3.2.1]oct-3-en-2-yl]molybdenum, (±)-95c.

Following the general procedure, to a THF (8 mL) solution of the molybdenum complex *anti*-**89g** (48 mg, 0.09 mmol, 1 equiv) was added NaH (7.2 mg, 0.18 mmol, 2 equiv). The reaction mixture was stirred at room temperature for 5 h, then cooled to 0 ^{o}C followed by addition of solid Me_3OBF_4 (26.6 mg, 0.18 mmol, 2 equiv). The resulting mixture was stirred for 40 min at 0 ^{o}C, and quenched with Et_3N (1 mL). After work up, the crude product was purified by flash chromatography on silica gel eluting with hexanes-EtOAc (2 : 1) to afford **95c** (49 mg, 99%) as a yellow solid.

(±)-**95c**: TLC (R_f = 0.60, hexanes-EtOAc 2:1). IR (cm^{-1}): 2972 (w), 2941 (w), 2482 (w), 1930 (s), 1841 (s), 1505 (m), 1409 (m), 1305 (m), 1216 (s). ^{1}H NMR (600 MHz, $CDCl_3$): δ 8.47 (d, J = 2.4 Hz, 1H), 7.99 (d, J = 2.4 Hz, 1H), 7.61 (m, 3H), 7.49 (d, J = 1.2 Hz, 1H), 6.24 (t, J = 2.4 Hz, 1H), 6.21 (t, J = 2.1 Hz, 1H), 6.16 (t, J = 2.4 Hz, 1H), 4.57 (dd, J

= 3.6, 1.2 Hz, 1H), 4.01 (td, *J* = 7.2, 3.6 Hz, 1H), 3.96 (d, *J* = 7.8 Hz, 1H), 3.80 (dd, *J* = 7.8, 2.1 Hz, 1H), 3.16 (s, 3H), 1.90-1.69 (m, 2H),1.69 (s, 3H), 1.09 (t, *J* = 7.2 Hz, 3H). ^{13}C NMR (150 MHz, $CDCl_3$): δ 233.0, 228.9, 146.1, 144.9, 141.0, 136.5, 135.8, 134.3, 126.9, 107.9, 105.6, 105.5, 105.4, 82.0, 77.7, 64.6, 58.8, 54.4, 23.0, 22.5, 10.9. HRMS (ESI) Calcd for $C_{21}H_{26}BMoN_6O_5$ ($[M+H]^+$): 551.1106. Found: 551.1103.



100

(±)-Dicarbonyl[hydridotris(1-pyrazolyl)borato][(1*S*,3*R*,5*S*,7*R*)-η-(3,4)-7-methyl-5-oxo-6,8-dioxabicyclo[3.2.1]oct-3-en-3-yl]molybdenum, (±)-100.

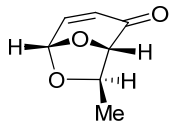
To a Schlenk flask charged with (±)-*syn*-**89a** (141 mg, 0.28 mmol, 1 equiv) in dry THF (6 mL) was added NaH (60% dispersed in mineral oil, 22.4 mg, 0.56 mmol, 2 equiv) under argon. After being stirred for 30 min at room temperature, the reaction mixture was cooled to -15 ^{o}C followed by addition of $NOPF_6$ (153 mg, 1.11 mmol, 4.0 equiv) as a solid. The orange solution turned yellowish brown immediately with vigorous bubbling. After 5 min at -20 ^{o}C, the reaction was opened to air, and the cold bath was removed. The reaction was allowed to slowly warm to room temperature and stirred for 45 min. Then the reaction mixture was directly subjected to column chromatography on silica gel (hexanes-EtOAc 2:1) to afford **100** (64 mg, 45%) as a yellow solid.

(±)-**100**: TLC (R_f = 0.33, hexanes-EtOAc 2:1). IR (cm^{-1}): 2494 (m), 2011 (s), 1679 (s),

1660 (s), 1505 (s), 1409 (s), 1305 (s), 1243 (s). ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.16 (d, *J* = 2.0 Hz, 1H), 8.01 (d, *J* = 2.0 Hz, 1H), 7.72 (d, *J* = 2.4 Hz, 1H), 7.70 (d, *J* = 2.4 Hz, 1H), 7.62 (d, *J* = 1.6 Hz, 1H), 7.21 (d, *J* = 2.0 Hz, 1H), 6.44 (m, 2H), 6.24 (s, 1H), 6.12 (t, *J* = 2.2 Hz, 1H), 4.37 (qd, *J* = 6.2, 1.0 Hz, 1H), 4.17 (d, *J* = 1.2 Hz, 1H), 3.72 (dd, *J* = 8.8, 1.6 Hz, 1H), 3.00 (dd, *J* = 8.8, 0.6 Hz, 1H), 1.36 (d, *J* = 6.0 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 217.2, 204.0, 144.0, 143.8, 140.9, 136.8, 136.0, 135.5, 106.4, 106.1, 105.8, 103.1, 84.5, 74.9, 72.4, 58.4, 20.6. HRMS (ESI) Calcd for $C_{17}H_{19}BMoN_7O_5$([M+H]$^+$): 510.0589. Found: 510.0589.

General procedure for intramolecular 1,5-Michael reaction and demetalation cascade.

To a Schlenk flask charged with *syn*-**89** or *anti*-**89** (1 equiv) in dry dimethoxyethane was added NaH (60% dispersed in mineral oil, 2 equiv) under argon. After being stirred for 2 to 6 h at room temperature, the reaction mixture was cooled to -20 ^{o}C followed by addition of $NOPF_6$ or $NOBF_4$ (4.0 equiv) as a solid. The orange solution turned brown immediately with vigorous bubbling. After 5 min at -20 ^{o}C, the reaction was opened to air, and the cold bath was removed. The reaction was allowed to slowly warm to room temperature and stirred for additional 30 min. Then the reaction mixture was washed immediately with CH_2Cl_2 and H_2O. The aqueous layer was separated and extracted with CH_2Cl_2. The combined organic layers were washed with brine, dried over $MgSO_4$, filtered, concentrated, and purified by column chromatography on silica gel.



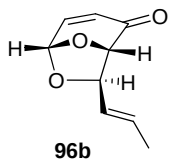
(-)-**96a**

(-)-(1*S*,5*S*,7*R*)-7-methyl-6,8-dioxabicyclo[3.2.1]oct-3-en-2-one, (-)-96a.

Following the general procedure, (-)-*syn*-**89a** (125 mg, 0.25 mmol, 1 equiv) was dissolved in dry DME (8 mL), and reacted with NaH (60% dispersed in mineral oil, 20 mg, 0.5 mmol, 2 equiv) for 2 h followed by adding $NOBF_4$ (121 mg, 0.98 mmol, 4 equiv). Purification by column chromatography on silica gel (hexanes-EtOAc 3:1) afforded (-)-**96a** (28 mg, 98.7% ee, 81%) as a colorless oil.

(-)-96a: TLC (R_f = 0.59, hexanes-EtOAc 2: 1). IR (cm^{-1}): 2926 (w), 1695 (s), 1046 (w), 934 (m). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.10 (dd, *J* = 9.6, 3.2 Hz, 1H), 6.05 (dt, *J* = 9.6, 1.2 Hz, 1H), 5.82 (d, *J* = 2.8 Hz, 1H), 4.32 (t, *J* = 1.4 Hz, 1H), 4.03 (qd, *J* = 6.4, 1.2 Hz, 1H), 1.39 (d, *J* = 6.0 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 194.7, 147.6, 126.6, 96.6, 85.0, 70.8, 19.9. HRMS (ESI) Calcd for $C_7H_9O_3$ ($[M+H]^+$): 141.0546. Found: 141.0544.

(-)-**96a:** $[\alpha]_D^{20}$ = -230.1 (*c* = 1.35, CH_2Cl_2). HPLC: CHIRALPAK AS-RH column, CH_3CN : H_2O with 0.1% TFA = 10 : 90, 0.5 mL/min., λ = 254 nm, t_R = 22.33 min, 98.7% ee. Enantiomer: t_R = 18.19 min.

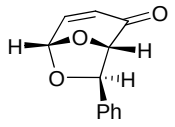


96b

(±)-**(1*S*,5*S*,7*R*)-7-[(*E*)-prop-1-enyl]-6,8-dioxabicyclo[3.2.1]oct-3-en-2-one**, **(±)-96b**.

Following the general procedure, *syn*-**89c** (92 mg, 0.17 mmol, 1 equiv) was dissolved in dry DME (5 mL), and reacted with NaH (60% dispersed in mineral oil, 13.8 mg, 0.34 mmol, 2 equiv) for 3 h followed by adding $NOPF_6$ (125 mg, 0.69 mmol, 4 equiv). Purification by column chromatography on silica gel (hexanes-EtOAc 3:1) afforded **96b** (16 mg, 56%) as a colorless oil.

(±)-**96b**: TLC (R_f = 0.75, hexanes-EtOAc 2:1). IR (cm^{-1}): 2918 (m), 1698 (s), 1451 (w), 1374 (m), 1247 (m). ^1H NMR (400 MHz, $CDCl_3$): δ 7.13 (dd, *J* = 9.6, 2.8 Hz, 1H), 6.06 (d, *J* = 10.0, 1H), 5.86 (d, *J* = 2.8 Hz, 1H), 5.84 (m, 1H), 4.92 (ddq, *J* = 8.4, 8.2, 1.6 Hz, 1H), 4.44 (t, *J* = 1.4 Hz, 1H), 4.26 (d, *J* = 8.0 Hz, 1H), 1.74 (dd, *J* = 6.4, 1.6 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 194.4, 147.6, 131.1, 127.2, 126.6, 96.7, 84.6, 75.5, 17.7. HRMS (ESI) Calcd for $C_9H_{11}O_3$ ($[M+H]^+$): 167.0703. Found: 167.0699.



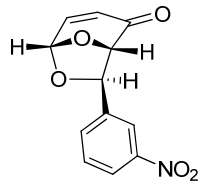
96c

(±)-(1*S*,5*S*,7*R*)-7-phenyl-6,8-dioxabicyclo[3.2.1]oct-3-en-2-one, **(±)-96c**.

Following the general procedure, *syn*-**89d** (50 mg, 0.09 mmol, 1 equiv) was dissolved in dry DME (5 mL), and reacted with NaH (60% dispersed in mineral oil, 7 mg, 0.18 mmol, 2 equiv) for 3 h followed by adding $NOPF_6$ (63.3 mg, 0.35 mmol, 4 equiv). Purification by column chromatography on silica gel (hexanes-EtOAc 4:1) afforded **96c** (10 mg, 56%) as a colorless oil.

(±)-**96c**: TLC (R_f = 0.65, hexanes-EtOAc 3: 1). IR (cm^{-1}): 2922 (w), 1695 (s), 1494 (w),

1455 (w), 1374 (w). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.35(m, 5H), 7.23 (dd, *J* = 9.6, 3.6 Hz, 1H), 6.15 (dd, *J* = 9.6, 0.8 Hz, 1H), 4.86 (d, *J* = 1.2 Hz, 1H), 4.57 (d, *J* = 1.2 Hz, 1H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 194.0, 147.6, 138.4, 128.7 (2C), 128.6, 126.7, 126.3 (2C), 97.3, 86.6, 76.0. HRMS (ESI) Calcd for $C_{12}H_{11}O_3$ ($[M+H]^+$): 203.0703. Found: 203.0703.

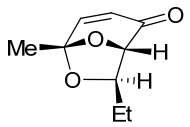


96d

(±)-**(1*S*,5*S*,7*R*)-7-(3-nitrophenyl)-6,8-dioxabicyclo[3.2.1]oct-3-en-2-one, (±)-96d**.

Following the general procedure*, syn*-**89e** (82 mg, 0.13 mmol, 1 equiv) was dissolved in dry DME (5 mL), and reacted with NaH (60% dispersed in mineral oil, 10.7 mg, 0.26 mmol, 2 equiv) for 3 h followed by adding $NOPF_6$ (96.5 mg, 0.52 mmol, 4 equiv). Purification by column chromatography on silica gel (hexanes-EtOAc 3:1) afforded **96d** (7 mg, 21%) as a white solid.

(±)-**96d**: TLC (R_f = 0.54, hexanes-EtOAc 3: 1). IR (cm^{-1}): 2922 (m), 1695 (s), 1529 (s), 1347 (s), 1251 (s). ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.27 (t, *J* = 2.0 Hz, 1H), 8.21 (ddd, *J* = 8.0, 2.4, 1.2 Hz, 1H), 7.70 (d, *J* = 7.6 Hz, 1H), 7.57 (t, *J* = 8.4 Hz, 1H), 7.28 (dd, *J* = 9.6, 3.2 Hz, 1H), 6.19 (dd, *J* = 9.6, 1.2 Hz, 1H), 6.16 (d, *J* = 3.2 Hz, 1H), 4.95 (s, 1H), 4.56 (t, *J* = 1.4 Hz, 1H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 193.1, 148.4, 147.6, 140.8, 132.2, 129.8, 126.9, 123.5, 121.3, 97.5, 86.4, 75.1. HRMS (ESI) Calcd for $C_{12}H_{10}NO_5$ ($[M+H]^+$): 248.0554. Found: 248.0550.

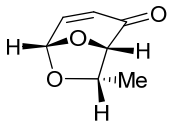


96e

(±)-(1*S*,5*S*,7*R*)-7-ethyl-5-methyl-6,8-dioxabicyclo[3.2.1]oct-3-en-2-one, **(±)-96e**.

Following the general procedure, ***syn*-89g** (210 mg, 0.39 mmol, 1 equiv) was dissolved in dry DME (10 mL), and reacted with NaH (60% dispersed in mineral oil, 31 mg, 0.78 mmol, 2 equiv) for 2 h followed by adding $NOPF_6$ (287 mg, 1.57 mmol, 4 equiv). Purification by column chromatography on silica gel hexanes-EtOAc 4:1) afforded **96e** (40 mg, 73 %) as a light yellow oil.

(±)-**96e**: TLC (R_f = 0.50, hexanes-EtOAc 4: 1). IR (cm^{-1}): 2968 (m), 2926 (m), 1702 (s), 1390 (s), 1254 (s), 1108 (s), 1034 (s). ^{1}H NMR (600 MHz, $CDCl_3$): δ 6.95 (d, *J* = 10.2 Hz, 1H), 6.00 (dd, *J* = 10.2, 2.1Hz, 1H), 4.33 (t, *J* = 1.2 Hz, 1H), 3.75 (dt, *J* = 6.0, 1.8 Hz, 1H), 1.69 (m, 2H), 1.69 (s, 3H), 0.98 (t, *J* = 7.2 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 195.1, 150.8, 125.7, 103.5, 84.1. 77.0, 27.1, 21.9, 9.6. HRMS (ESI) Calcd for $C_9H_{13}O_3$ ($[M+H]^+$): 169.0859. Found: 169.0855.



(-)-**97a**

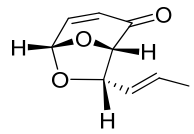
(-)-(1*S*,5*S*,7*S*)-7-methyl-6,8-dioxabicyclo[3.2.1]oct-3-en-2-one, (-)-97a.

Following the general procedure, (-)-*anti*-**89a** (120 mg, 0.24 mmol, 1 equiv) was dissolved in dry DME (8 mL), and reacted with NaH (60% dispersed in mineral oil, 19

mg, 0.48 mmol, 2 equiv) for 5 h followed by adding $NOBF_4$ (120 mg, 0.97 mmol, 4 equiv). Purification by column chromatography on silica gel (hexanes-EtOAc 3:1) afforded (-)-**97a** (23 mg, 98.7% ee, 70%) as a colorless oil.

(-)-**97a**: TLC (R_f = 0.59, hexanes-EtOAc 2: 1). IR (cm^{-1}): 2984 (m), 2922 (m), 1702 (s), 1374 (s), 1239 (s). ^1H NMR (400 MHz, $CDCl_3$): δ 7.29 (dd, *J* = 9.6, 3.2 Hz, 1H), 6.10 (dt, *J* = 7.6, 1.0 Hz, 1H), 5.70 (d, *J* = 3.2 Hz, 1H), 4.70 (dd, *J* = 5.8, 1.0 Hz, 1H), 4.38 (m, 1H), 1.17 (d, *J* = 6.8 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 194.1, 150.3, 127.9, 95.7, 83.4, 71.1, 15.7. HRMS (ESI) Calcd for $C_7H_9O_3$ ($[M+H]^+$): 141.0546. Found: 141.0550.

(-)-**97a**: $[\alpha]_D^{20}$ = -573.6° (*c* = 1.05, CH_2Cl_2). HPLC: CHIRALPAK AS-RH column, CH_3CN : H_2O with 0.1% TFA = 10 : 90, 0.5 mL/min., λ = 254 nm, t_R = 25.12 min, 98.7% ee. Enantiomer: t_R = 20.00 min.



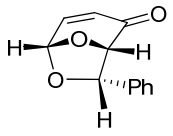
97b

(±)-(1*S*,5*S*,7*S*)-7-((*E*)-prop-1-enyl)-6,8-dioxabicyclo[3.2.1]oct-3-en-2-one, **(±)-97b**.

Following the general procedure*, anti*-**89c** (80 mg, 0.15 mmol, 1 equiv) was dissolved in dry DME (5 mL), and reacted with NaH (60% dispersed in mineral oil, 12 mg, 0.30 mmol, 2 equiv) for 3 h followed by adding $NOPF_6$ (108 mg, 0.60 mmol, 4 equiv). Purification by column chromatography on silica gel (hexanes-EtOAc 4:1) afforded **97b** (11 mg, 44 %) as a colorless oil.

(±)-**97b**: TLC (R_f = 0.44, hexanes-EtOAc 4:1). IR (cm^{-1}): 2922 (m), 1702 (s), 1447

(w), 1374 (m), 1212(s). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.28 (dd, *J* = 9.6, 3.2 Hz, 1H), 6.10 (d, *J* = 9.6, 1H), 5.86 (d, *J* = 2.8 Hz, 1H), 5.84 (dt, *J* = 14.8, 6.8 Hz 1H), 5.75 (d, *J* = 3.2 Hz, 1H), 5.11 (ddq, *J* = 7.4, 7.4, 1.2 Hz, 1H), 4.74-4.66 (m, 1H), 1.67 (dd, *J* = 6.8, 1.2 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 193.7, 149.7, 133.2, 128.2, 124.2, 96.0, 83.2, 76.3, 17.8. HRMS (ESI) Calcd for $C_9H_{11}O_3$ ($[M+H]^+$): 167.0703. Found: 167.0699.

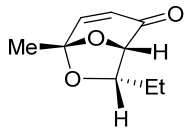


97c

(±)-(1*S*,5*S*,7*S*)-7-phenyl-6,8-dioxabicyclo[3.2.1]oct-3-en-2-one, **(±)-97c**.

Following the general procedure*,* *anti*-**89d** (83 mg, 0.146 mmol, 1 equiv) was dissolved in dry DME (5 mL), and reacted with NaH (60% dispersed in mineral oil, 11.6 mg, 0.29 mmol, 2 equiv) for 6 h followed by adding $NOPF_6$ (105 mg, 0.58 mmol, 4 equiv). Purification by column chromatography on silica gel (hexanes-EtOAc 4:1) afforded **97c** (18 mg, 61%) as a colorless oil and **96c** (5 mg, 17%) as a colorless oil.

(±)-**97c**: TLC (R_f = 0.79, hexanes-EtOAc 2: 1). IR (cm^{-1}): 1710 (s), 1235 (w), 1069 (s), 984 (m), 907 (s). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.34 (dd, *J* = 9.6, 3.2 Hz, 1H), 7.31-7.19 (m, 5H), 5.97 (d, *J* = 9.6 Hz, 1H), 5.96 (d, *J* = 2.8 Hz, 1H), 5.47 (d, *J* = 6.4 Hz, 1H), 4.99 (dd, *J* = 6.0, 1.2 Hz, 1H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 192.6, 148.5, 134.3, 129.1, 128.4 (2C), 128.2, 125.8 (2C), 96.7, 84.4, 76.8. HRMS (ESI) Calcd for $C_{12}H_{11}O_3$ ($[M-H]^+$): 201.0542. Found: 201.0542.

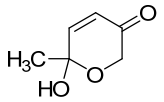


97d

(±)-(1*S*,5*S*,7*S*)-7-ethyl-5-methyl-6,8-dioxabicyclo[3.2.1]oct-3-en-2-one, **(±)-97d.**

Following the general procedure*, anti*-**89g** (170 mg, 0.32 mmol, 1 equiv) was dissolved in dry DME (8 mL), and reacted with NaH (60% dispersed in mineral oil, 26 mg, 0.65 mmol, 2 equiv) for 6 h followed by adding $NOPF_6$ (232 mg, 1.28 mmol, 4 equiv). Purification by column chromatography on silica gel (hexanes/EtOAc 3:1) afforded **97d** (35 mg, 66 %) as a colorless oil.

(±)-**97d**: TLC (R_f = 0.66, hexanes-EtOAc 2: 1). IR (cm^{-1}): 2968 (m), 2941 (m), 1695 (s), 1556 (s), 1386 (s). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.12 (d, *J* = 9.62 Hz, 1H), 6.04 (dd, *J* = 9.6, 1.2 Hz, 1H), 4.69 (dd, *J* = 6.0, 1.2 Hz, 1H), 4.20 (qd, *J* = 6.0, 1.8 Hz, 1H), 1.66 (s, 3H), 1.43 (m, 2H), 0.95 (t, *J* = 7.4 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 194.2, 153.6, 127.2, 102.7, 83.7. 78.1, 23.8, 22.2, 10.7. HRMS (ESI) Calcd for $C_9H_{13}O_3$ ($[M+H]^+$): 169.0859. Found: 169.0855.



101

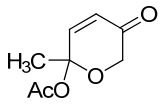
(±)-6-Hydroxy-6-methyl-6*H*-pyran-3-one, (±)-101.

5-Methyl-2-furanmethanol[82] (5.0 g, 44.6 mmol, 1.0 equiv.) was dissolved in CH_2Cl_2

[82] 5-Methyl-2-furanmethanol was purchased from Aldrich, and used directly.

(100 mL) at 0 °C. Then *m*-CPBA (77%, 10.5 g, 46.8 mmol, 1.05 equiv) was added to the reaction portion by portion (5 g each). After stirring at 0 °C for 15 min, the reaction was slowly warmed to room temperature, and stirred for 1 hr. Then the mixture was cooled to -78 °C, and the solid was vacuum filtered at low temperature. The filtrate was concentrated on a rotary evaporator, and purified by column chromatography on silica gel (hexanes-EtOAc 1:1) to afford **101** as a yellow solid (5.6 g, 98%).

(±)-101. ^{1}H NMR (600 MHz, $CDCl_3$): δ 6.86 (d, J = 9.6 Hz, 1H), 6.03 (d, J = 10.8 Hz, 1H), 4.53 (d, J = 16.8 Hz, 1H), 4.09 (d, J = 16.8 Hz, 1H), 3.76 (br s, 1H), 1.61 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) : δ 195.3, 149.3, 126.2, 92.7, 66.4, 27.6.



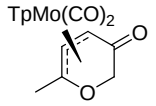
102

(±)-2-methyl-5-oxo-5,6-dihydro-2*H*-pyran-2-yl acetate, (±)-102.

In a 250 mL flask with **101** (4.7 g, 36.7 mmol, 1.0 equiv) under argon, CH_2Cl_2 was added until all solid was dissolved. After cooling the solution to 0 °C, Et_3N (5.38 mL, 38.6 mmol, 1.05 equiv.), Ac_2O (3.79 mL, 40.4 mmol, 1.1 equiv) and a crystal of DMAP were added to the reaction respectively. After stirring at 0 °C for 2 hr, the reaction was slowly warmed to room temperature and stirred for 15min. Then the mixture was purged into a separatory funnel and washed with saturated $NaHCO_3$ (100 mL) and CH_2Cl_2 (50 mL). The organic layers were collected and washed with brine (50 mL), dried over $MgSO_4$, filtered, and concentrated to afford a deep red oil (5.0g, 81%), which was used

directly in the next step without further purification.

(±)-**102**: ^{1}H NMR (300 MHz, $CDCl_3$): δ 6.34 (d, J = 10.2 Hz, 1H), 6.08 (d, J = 10.2 Hz, 1H), 4.58 (d, J = 17.4 Hz, 1H), 4.21 (d, J = 17.1 Hz, 1H), 2.06 (s, 3H), 1.80 (s, 3H).



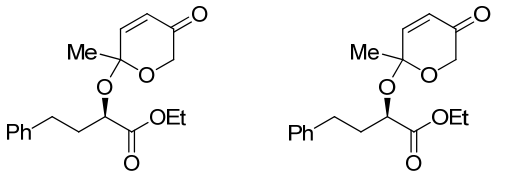
(±)-**88**

(±)-Dicarbonyl[hydridotris(1-pyrazolyl)borato][η-(2,3,4)-2-methyl-5-oxo-5,6-dihydro-2*H*-pyran-2-yl]molybdenum, (±)-88.

To a Schlenk flask charged with a solution of $Mo(CO)_3(DMF)_3$ (5.5 g, 5.87 mmol, 1.2 equiv) in degassed, dry CH_2Cl_2 (40 mL) under argon was slowly added a solution of **102** (1.95 g, 5.87 mmol, 1.0 equiv) in degassed CH_2Cl_2 (10 mL) at room temperature. The reaction mixture was stirred for 2.5 h, and then solid KTp (3.49 g, 5.87 mmol, 1.2 equiv) was added in one portion. After stirring for 1 h at room temperature, the solution was passed through a pad of silica gel with EtOAc. The solvents were completely removed on a rotary evaporator, and the residue was purified by column chromatography on silica gel (hexanes-EtOAc 1:1) to afford a brown solid (±)-**88** (3.1 g, 57%).

(±)-**88**: TLC (R_f = 0.32, hexanes-EtOAc 2:1). IR (cm^{-1}): 2486 (w), 2250 (w), 1934 (s), 1841 (s), 1637(s), 1521(m), 1305 (m), 1220 (m), 1123 (m). ^{1}H NMR (600 MHz, $CDCl_3$): δ 8.44 (br s, 1H), 8.30 (br s, 1H), 7.60 (br s, 4H), 6.22 (s, 3H), 4.85 (d, J = 6.0 Hz, 1H), 4.47 (d, J = 6.0 Hz, 1H), 3.76 (s, 2H), 2.60 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 239.7, 227.6, 189.9, 147.5, 146.7, 144.7, 142.4, 136.3, 135.5, 134.5, 105.9(3), 72.7, 68.6, 67.2,

24.3. HRMS (ESI) Calcd for $C_{17}H_{18}BMoN_6O_4$ ([M+H]$^+$): 479.0531. Found: 479.0530.



less polar
faster eluting isomer
104a

more polar
slower eluting isomer
104b

(2*R*)-ethyl 2-(2-methyl-5-oxo-5,6-dihydro-2*H*-pyran-2-yloxy)-4-phenylbutanoate, 104a and **104b.**

To a 100 mL flask charged with 6-hydroxy-6-methyl-6*H*-pyran-3-one **101** (1.75 g, 13.7 mmol, 1.1 equiv), ethyl (*R*)-(-)-2-hydroxy-4-phenylbutyrate[83] (2.59 g, 12.4 mmol, 1 equiv) and activated 4 Å molecular sieves under argon was added dry CH_2Cl_2 (20 mL). The solution was cooled to -78 ^oC, and $BF_3{\cdot}Et_2O$ (1.7 mL, 1.92 g, 13.6 mmol, 1 equiv) was added. After stirring at -78 ^oC for 1 h, the reaction was quenched with adding Et_3N (3.47 mL, 24.9 mmol, 2 equiv). Then reaction mixture was stirred for 15 min at -78 ^oC, then directly filtered through a short pad of Celite with EtOAc and concentrated. The residue was passed through a short silica gel column, and eluted with 20% EtOAc in hexanes. Solvents were completely removed on a rotary evaporator, and the crude material was further purified by column chromatography on silica gel (hexanes-EtOAc 9:1) to afford the less polar diastereomer **104a** (1.63 g, 41%), and more polar diastereomer **104b** (1.71g, 43%) as colorless oils. *Additional 1 to 2 times column chromatography under*

[83] Ethyl (*R*)-(-)-2-hydroxy-4-phenylbutyrate was purchsed from Aldrich, and used directly.

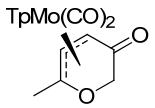
*same condition were performed to obtain **104a** and **104b** for >99% ee.*

104a: TLC (R_f = 0.50, hexanes-EtOAc 4:1). IR (cm^{-1}): 1741 (s), 1695 (s), 1455 (m), 1382 (m), 1282 (m). ^1H NMR (400 MHz, $CDCl_3$): δ 7.29 (m, 3H), 7.21 (m, 2H), 6.81 (d, *J* = 10.8 Hz, 1H), 6.10 (d, *J* = 10.4 Hz, 1H), 4.55 (d, *J* = 17.2 Hz, 1H), 4.31 (t, *J* = 6.4 Hz, 1H), 4.19 (m, 2H), 3.99 (d, *J* = 17.2 Hz, 1H), 2.72 (m, 2H), 2.07 (m, 2H), 1.54 (s, 3H), 1.29 (t, *J* = 7.0 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 194.4, 172.5, 148.0, 140.8, 128.5 (2C), 128.4 (2C), 126.7, 126.1, 96.5, 70.8, 67.3, 61.1, 34.8, 31.2, 23.6, 14.2. HRMS (ESI) Calcd for $C_{18}H_{26}NO_5$ ($[M+NH_4]^+$): 336.1807. Found: 336.1806.

104a: $[\alpha]_D^{20}$ = -20.8 (*c* = 1.395, CH_2Cl_2). HPLC: CHIRALPAK OJ-RH column, CH_3CN : H_2O = 40 : 60, 0.9 mL/min., λ = 254 nm, t_R = 16.30 min, >99% ee.

104b: TLC (R_f = 0.42, hexanes-EtOAc 4:1). IR (cm^{-1}): 1749 (s), 1695 (s), 1455 (m), 1382 (m), 1282 (m). ^1H NMR (400 MHz, $CDCl_3$): δ 7.29 (m, 3H), 7.19 (m, 2H), 6.85 (d, *J* = 10.4 Hz, 1H), 6.10 (d, *J* = 10.4 Hz, 1H), 4.36 (t, *J* = 6.2 Hz, 1H),4.36 (d, *J* = 16.8 Hz, 1H), 4.21 (qd, *J* = 6.8, 0.8 Hz, 2H), 4.08 (d, *J* = 16.8 Hz, 1H), 2.71 (m, 2H), 2.08 (m, 2H), 1.51 (s, 3H), 1.29 (t, *J* = 7.2 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 194.0, 172.5, 148.5, 140.7, 128.5 (2C), 128.3 (2C), 126.8, 126.2, 96.5, 70.9, 66.9, 61.0, 35.1, 31.3, 23.5, 14.2. HRMS (ESI) Calcd for $C_{18}H_{23}O_5$ ($[M+H]^+$): 319.1542. Found: 319.1540.

104b: $[\alpha]_D^{20}$ = -22.2 (*c* = 1.55, CH_2Cl_2). HPLC: CHIRALPAK OJ-RH column, CH_3CN : H_2O = 40 : 60, 0.9 mL/min., λ = 254 nm, t_R = 12.70 min, >99% ee.



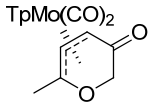
(-)-88

(-)-Dicarbonyl[hydridotris(1-pyrazolyl)borato][(2*S*)-η-(2,3,4)-2-methyl-5-oxo-5,6-dihydro-2*H*-pyran-2-yl]molybdenum, (-)-88.

In a 100 mL Schlenk flask, $Mo(CO)_3(DMF)_3$ (0.289 g, 0.72 mmol, 1 equiv) was dissolved in freshly degassed dry CH_2Cl_2 (75 mL) at room temperature under argon for 5 min. Then the $Mo(CO)_3(DMF)_3$ solution was cooled to -78 ^oC. *Via* a cannula, the $Mo(CO)_3(DMF)_3$ solution was added dropwise to a 200 mL Schlenk flask charged with a vigorous stirred solution of **104a** (0.35 g, 1.1 mmol, 1.4 equiv) in freshly degassed dry CH_2Cl_2 (50 mL) under argon over 45 min at room temperature. Upon addition of the $Mo(CO)_3(DMF)_3$ solution, the reaction mixture was stirred for 1 h at room temperature, then solid potassium hydridotris(1-pyrazolyl)borate (KTp) (0.37 g, 1.47 mmol, 2 equiv) was added in one portion. After stirring for 1 hour at room temperature, the reaction solution was directly passed through a pad of silica gel, eluting with EtOAc. The solvents were completely removed on a rotary evaporator, and the residue was further purified by column chromatography on silica gel (hexanes-EtOAc 1:1) to afford a brown solid (-)-**88** (0.135 g, 40%) in 81% ee. Meanwhile, 0.22g **104a** was recovered without loss of enantiopurity. *Complex (-)-**88** tends to crystallize as a single enantiomer, therefore slow crystallization in hexanes/CH_2Cl_2 afforded the product in >98% ee when the crystals formed were collected, and the filtrate was removed.*

*Characterization as in (±)-**88**.*

(-)-**88**: $[\alpha]_D^{20}$ = -346 (*c* = 0.025, CH_2Cl_2). HPLC: CHIRALPAK AS-RH column, CH_3CN : H_2O with 0.1% TFA = 50 : 50, 1.0 mL/min., λ = 254 nm, t_R = 14.95 min, >98% ee. Enantiomer: t_R = 8.53 min



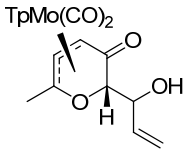
(+)-88

(+)-Dicarbonyl[hydridotris(1-pyrazolyl)borato][(2-*R*)-*η*-(2,3,4)-2-methyl-5-oxo-5,6-dihydro-2*H*-pyran-2-yl]molybdenum, (+)-88.

In a 100 mL Schlenk flask, $Mo(CO)_3(DMF)_3$ (0.163 g, 0.40 mmol, 1 equiv) was dissolved in degassed dry CH_2Cl_2 (50 mL) at room temperature under argon for 5 min. Then the $Mo(CO)_3(DMF)_3$ solution was cooled to -78 ^oC. *Via* a cannula, the cold $Mo(CO)_3(DMF)_3$ solution was added dropwise to a 200 mL Schlenk flask charged with a vigorous stirring solution of **104b** (0.20 g, 0.62 mmol, 1.55 equiv) in degassed dry CH_2Cl_2 (35 mL) under argon over 30 min at room temperature. Upon addition of the $Mo(CO)_3(DMF)_3$ solution, the reaction mixture was stirred for 1 h at room temperature, then solid potassium hydridotris(1-pyrazolyl)borate (KTp) (0.158 g, 0.62 mmol, 1.55 equiv) was added in one portion. After stirring for 1 hour at room temperature, the reaction solution was directly passed through a pad of silica gel, eluting with EtOAc. The solvents were completely removed on a rotary evaporator, and the residue was further purified by column chromatography on silica gel (EtOAc-hexanes 1:1) to afford a brown solid (+)-**88** (0.036 g, 18%) in 93% ee.

*Characterization as in (±)-**88**.*

(+)-**88:** $[\alpha]_D^{20}$ = +112 (*c* = 0.02, CH_2Cl_2). HPLC: CHIRALPAK AS-RH column, CH_3CN : H_2O with 0.1% TFA = 50 : 50, 1.0 mL/min., λ = 254 nm, t_r = 8.53 min, 93% ee. Enantiomer: t_r = 14.95 min



(-)-89h

Dicarbonyl[hydridotris(1-pyrazolyl)borato][(2*S*,6*S*)-η-(2,3,4)-2-methyl-6-(1-hydroxylpropen-2-yl)-5-oxo-5,6-dihydro-2*H*-pyran-2-yl]molybdenum, 89h.

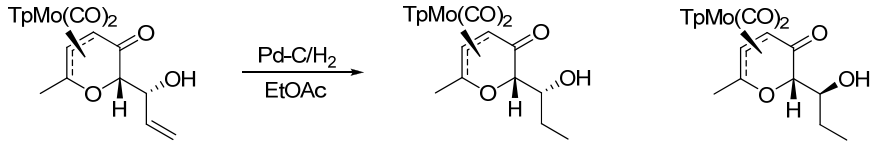
To a stirring solution of (-)-**88** (0.252 g, 98% ee, 0.53 mmol, 1 equiv) in dry CH_2Cl_2 (7 mL) was added LiHMDS (1.0 M in THF, 2.1 mL, 2.1 mmol, 4 equiv) at -90 ºC (MeOH/liquid N_2 bath). After being stirred at -90 ºC for 30 min, acrolein (0.7 mL) was added to the solution, and stirred for 10 min at -90 ºC followed by quenching with H_2O (1.5 mL) and diluting with Et_2O (7 mL). Then the reaction mixture was washed immediately with Et_2O (20 mL) and H_2O (20 mL). The aqueous layer was separated and extracted with Et_2O (20 mL). The combined organic layers were washed with brine (10 mL), dried over $MgSO_4$, filtered, concentrated, and purified by column chromatography on silica gel (CH_2Cl_2-EtOAc-hexanes 4:2:1) to afford brown solid **89h** (0.23 g, 82%) as a inseparable mixture of *syn* and *anti* isomers (*syn* : *anti* = 3 : 1).

The ratio of *syn* and *anti* was determined by HPLC. HPLC: Eclipse XDB-C8 (5 μm,

4.6 x 150 mm) column, CH_3CN : H_2O with 0.1% TFA = 50 : 50, 1.0 mL/min., λ = 254 nm, t_R(*anti*) = 6.18 min, t_R(*syn*) = 7.05 min.

*Since **89h** is an inseparable mixture of anti and syn isomers, the following NMR data of **89h** are only for reference.*

89h: TLC (R_f = 0.44, CH_2Cl_2-EtOAc-hexanes 4:2:1). IR (cm^{-1}): 3401 (w), 2482 (w), 1930 (s), 1830 (s), 1621 (s), 1521 (m), 1409 (m), 1305(s), 1216(s). ^{1}H NMR (600 MHz, $CDCl_3$): δ 8.44 (br s, 1H), 8.23 (br s, 1H), 7.57 (br, 4H), 6.21 (br s, 3H), 5.84 (m, 1H), 5.37 (d, *J* = 17.4 Hz, 1H), 5.27 (d, *J* = 10.2 Hz, 1H), 4.91 (d, *J* = 6.0 Hz, 1H), 4.50 (d, *J* = 6.0 Hz, 1H), 4.49 (m, 1H), 4.36 (t, *J* = 4.8 Hz, 0.3H), 3.79 (d, *J* = 3.6 Hz, 1H), 2.59 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 240.0, 239.6, 227.9, 227.3, 191.3, 190.3, 147.7, 146.9, 144.4, 144.3, 142.4, 136.3, 135.8, 135.7, 135.0, 134.5, 117.5, 117.4, 106.0 (3C), 81.0, 79.8, 73.7, 73.3, 73.1, 72.5, 67.5, 24.2. HRMS (ESI) Calcd for $C_{20}H_{22}BMoN_6O_5$ ($[M+H]^+$): 535.0793. Found: 535.0788.



89h (-)-*syn*-**89g** (-)-*anti*-**89g**

(-)-Dicarbonyl[hydridotris(1-pyrazolyl)borato]{(2*S*,6*S*)-η-(2,3,4)-6-[(*R*)-1-hydroxypropyl]-2-methyl-5-oxo-5,6-dihydro-2*H*-pyran-2-yl}molybdenum, (-)-*syn*-89g and

(-)-Dicarbonyl[hydridotris(1-pyrazolyl)borato]{(2*S*,6*S*)-η-(2,3,4)-6-[(*S*)-1-

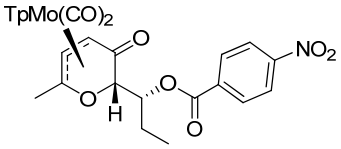
hydroxypropyl]-2-methyl-5-oxo-5,6-dihydro-2*H*-pyran-2-yl}molybdenum, (-)-*anti*-89g.

To a Schlenk flask equipped with a hydrogen balloon and charged with 124 mg Pd/C (10 wt %), **89h** (124 mg, 98% ee, 0.23 mmol, 1.0 equiv) was added dry EtOAc (4 mL). After stirring for 2 h at room temperature, the suspension was filtered through a short plug of Celite, concentrated, and purified by column chromatography on silica gel (CH_2Cl_2-EtOAc-hexanes 4:2:1) to afford (-)-*anti*-**89g** as a brown solid (28 mg, 98% ee, 22.5%), and (-)-*syn*-**89g** as a brown solid (85 mg, 98% ee, 68.5%).

*Characterization as in (±)-syn-**89g** and (±)-anti-**89g**.*

(-)-*syn*-**89g**: $[\alpha]_D^{20}$ = -328 (*c* = 0.02, CH_2Cl_2). HPLC: CHIRALPAK AS-RH column, CH_3CN : H_2O with 0.1% TFA = 40 : 60, 1.0 mL/min., λ = 254 nm, t_R = 17.58 min, >98% ee. Enantiomer: t_R = 21.62 min.

(-)-*anti*-**89g**: $[\alpha]_D^{20}$ = -331 (*c* = 0.055, CH_2Cl_2).



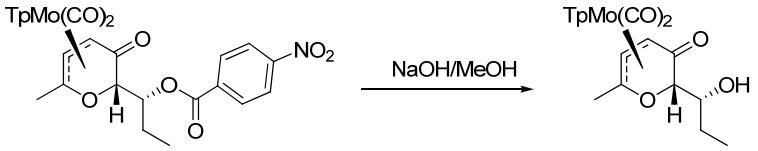
105

(±)-Dicarbonyl[hydridotris(1-pyrazolyl)borato]{(2*S*,6*S*)-η-(2,3,4)-2-methyl-6-[(*R*)-1-(4-nitrobenzoyloxy)propyl]-5-oxo-5,6-dihydro-2*H*-pyran-2-yl}molybdenum, (±)-105.

To a stirred solution of *anti*-**89g** (125 mg, 0.23 mmol, 1 equiv), Ph_3P (184 mg, 0.70 mmol, 3 equiv) and *p*-nitrobenzoic acid (117mg, 0.70 mmol, 3 equiv) in THF (10 mL) at

0 °C was added diethylazodicarboxylate (0.11 mL, 0.67 mmol, 2.9 equiv). After being stirred for 20 min at 0 °C, the reaction mixture was slowly warmed to room temperature and stirred for 2 h. Then the solution was concentrated under reduced pressure, and the residue was purified by column chromatography on silica gel eluting with hexanes-EtOAc (3:1) to afford **105** (135 mg, 84%) as a red-brown solid.

(±)-**105**: TLC (R_f = 0.51, hexanes : EtOAc = 2:1). IR (cm^{-1}): 3119 (w), 2976 (m), 2486 (m), 2250 (w), 1938 (s), 1845 (s), 1729 (s), 1640 (s), 1529 (s), 1409 (s). ^{1}H NMR (600 MHz, $CDCl_3$): δ 8.49 (br s, 1H), 8.31 (d, *J* = 8.4 Hz, 2H), 8.29 (br s, 1H), 8.23 (d, *J* = 8.4 Hz, 2H), 7.61-7.49 (br m, 4H), 6.22 (br s, 3H), 5.47 (td, *J* = 7.2, 2.6 Hz, 1H), 4.91 (d, *J* = 6.0 Hz, 1H), 4.55 (d, *J* = 6.0 Hz, 1H), 3.84 (d, *J* = 3.0 Hz, 1H), 2.68 (s, 3H), 1.92-1.78 (m, 2H), 0.98 (t, *J* = 7.2 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 240.5, 226.9, 189.4, 163.4, 150.5, 147.7 (br), 144.9 (br), 142.7, 142.2 (br), 136.3 (br), 135.6 (br), 135.4, 134.5 (br), 130.7 (2C), 123.7 (2C), 106.0 (br 2C), 105.5 (br), 78.3, 77.1, 73.5, 68.5, 24.3, 23.9, 9.7. HRMS (ESI) Calcd for $C_{27}H_{27}BMoN_6O_5$ ($[M+H]^+$): 686.1063. Found: 686.1059.

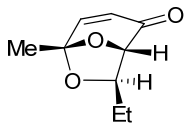


105 *syn*-**89g**

(±)-Dicarbonyl[hydridotris(1-pyrazolyl)borato]{(2*S*,6*S*)-η-(2,3,4)-6-[(*R*)-1-hydroxypropyl]-2-methyl-5-oxo-5,6-dihydro-2*H*-pyran-2-yl}molybdenum, (±)-*syn*-89g.

To a stirred suspension of **105** (24 mg, 0.035 mmol, 1 equiv) in MeOH (1 mL) was added solid NaOH (3.6 mg, 0.35 mmol, 10 equiv) at room temperature. The suspension slowly changed to a deep brown color solution. After being stirred for 5 min at room temperature, the reaction was quenched with saturated NH_4Cl, and extracted with Et_2O (2 x 10 mL). The combined organic layers were concentrated under reduced pressure. The residue was purified by flash chromatography on silica gel (CH_2Cl_2-EtOAc-hexanes 4:2:1) to afford *syn*-**89g** (11 mg, 59%) as a brown solid.

*Characterization as in (±)-syn-**89g***.



(-)-96e

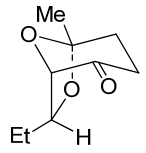
(-)-(1*S*,5*S*,7*R*)-7-ethyl-5-methyl-6,8-dioxabicyclo[3.2.1]oct-3-en-2-one, **(-)-96e**.

To a 25 mL Schlenk flask charged with (-)-*syn*-**89h** (200 mg, 98% ee, 0.375 mmol, 1 equiv) in dry dimethoxyethane (14 mL) was added NaH (60% dispersed in mineral oil) (30 mg, 0.75 mmol, 2 equiv) under argon. After stirred for 2.5 h at room temperature, the reaction mixture was cooled to -20 ^oC followed by adding $NOPF_6$ (273 mg, 1.50 mmol, 4 equiv) as a solid. The orange solution turned to brown immediately with vigorous bubbling. After 5 min at -20 ^oC, the reaction was opened to air, and slowly warmed to room temperature in 30 min. Then the reaction mixture was washed immediately with CH_2Cl_2 (15 mL) and H_2O (7 mL). The aqueous layer was separated and extracted with

CH_2Cl_2 (15 mL). The combined organic layers were washed with brine (10 mL), dried over $MgSO_4$, filtered, concentrated, and purified by column chromatography on silica gel (hexane-ethyl acetate 4 :1) to give (-)-**96e** as a slight yellow oil (46 mg, 98% ee, 73%).

*Characterization as in (±)-**96e**.*

(-)-**96e**: $[\alpha]_D^{20}$= -282.2 (*c* = 1.22, CH_2Cl_2). HPLC: CHIRALPAK AS-RH column, CH_3CN : H_2O with 0.1% TFA = 20 : 80, 0.8 mL/min., λ = 254 nm, t_R = 22.40 min, >98% ee. Enantiomer: t_R = 16.51 min



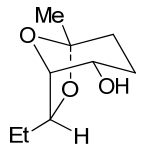
106

(+)-(1*S*,5*S*,7*R*)-7-ethyl-5-methyl-6,8-dioxabicyclo[3.2.1]octan-2-one, **(+)-106**.

To a Schlenk flask equipped with a hydrogen balloon and charged with 40 mg Pd/C (10 wt %) and compound (-)-**96e** (40 mg, 98% ee, 0.238 mmol, 1.0 equiv) was added dry EtOAc (2 mL). After stirring for 2 h at room temperature, the suspension was filtered through a short plug of Celite, concentrated, and purified by column chromatography on silica gel (hexanes-EtOAc 3:1) to afford (+)-**106** as a colorless oil (32 mg, 80%).

(+)-**106**: TLC (R_f = 0.42, hexane-EtOAc 3: 1). $[\alpha]_D^{20}$= +33.2 (*c* = 0.95, CH_2Cl_2). IR (cm^{-1}): 2964 (m), 2926 (m), 2853 (m), 1733 (s), 1463 (m), 1386 (m), 1266 (m), 1220 (m), 1173 (m). ^{1}H NMR (400 MHz, $CDCl_3$): δ 4.13 (s, 1H), 3.97 (t, *J* = 6.6 Hz, 1H), 2.56-2.39 (m, 2H), 2.17-2.03 (m, 2H), 1.58 (s, 3H), 1.67-1.48 (m, 2H), 0.93 (t, *J* = 7.4 Hz, 3H). ^{13}C

NMR (100 MHz, $CDCl_3$): δ 206.1, 107.9, 83.7, 80.3, 35.2, 32.6, 27.7, 24.3, 9.6. HRMS (ESI) Calcd for $C_9H_{18}NO_3$ ($[M+NH_4]^+$): 188.1281. Found: 188.1280.



107

(+)-(1*R*,2*S*,5*S*,7*R*)- 2-hydroxy-*exo*-brevicomin, (+)-107.

To a stirred solution of (+)-**106** (29 mg, 0.17 mmol, 1 equiv) in MeOH (2 mL) at 0 ^oC was added $NaBH_4$ (9.8 mg, 0.256 mmol, 1.5 equiv). After being stirred for 20 min at 0 ^oC, the reaction was quenched with H_2O (3 mL). The mixture was extracted with Et_2O (2 x 10 mL), and the combined extracts were dried over $MgSO_4$, and concentrated on the rotary evaporator. The residue was purified by column chromatography on silica gel (hexane-EtOAc 1:1) to afford (+)-(1*R*,2*S*,5*S*,7*R*)-2-hydroxy-*exo*-brevicomin **107** as a colorless oil (22 mg, 75%), and (1*R*,2*R*,5*S*,7*R*)-2- hydroxy-*exo*-brevicomin as a colorless oil (2 mg, 6.8%)

(+)-107: TLC (R_f = 0.51, hexanes-EtOAc 1:1). $[\alpha]_D^{20}$ = +40.3 (*c* = 1.10, $CHCl_3$). IR (cm^{-1}): 3432 (br m), 2961 (s), 2941 (s), 2880 (m), 1648 (w), 1463 (s), 1368 (s), 1239 (s), 1197 (s), 1173 (s). ^1H NMR (400 MHz, C_6D_6): δ 4.18 (t, *J* = 6.6 Hz, 1H), 3.80 (d, *J* = 3.6 Hz, 1H), 3.62 (m, 1H), 1.72-1.39 (m, 6H), 1.44 (s, 3H), 1.17 (br s, 1H), 0.91 (t, *J* = 7.6 Hz, 3H). ^{13}C NMR (100 MHz, C_6D_6): δ 107.4, 81.4, 77.7, 66.6, 35.8, 29.2, 27.3, 24.7, 10.4. HRMS (ESI) Calcd for $C_9H_{17}O_3$ ($[M+H]^+$): 173.1172. Found: 173.1170.

Chapter 3

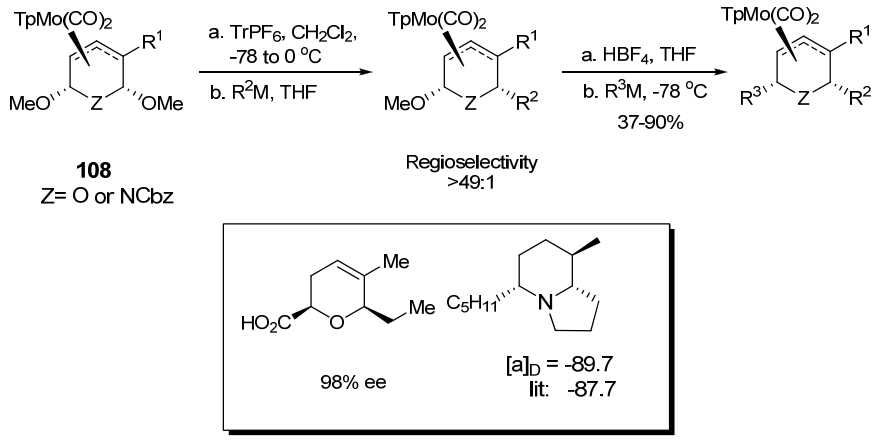
Synthesis of Highly Substituted Pyranones *via* a Molybdenum-mediated Intermolecular '1,5-Michael-like' Reaction

Introduction

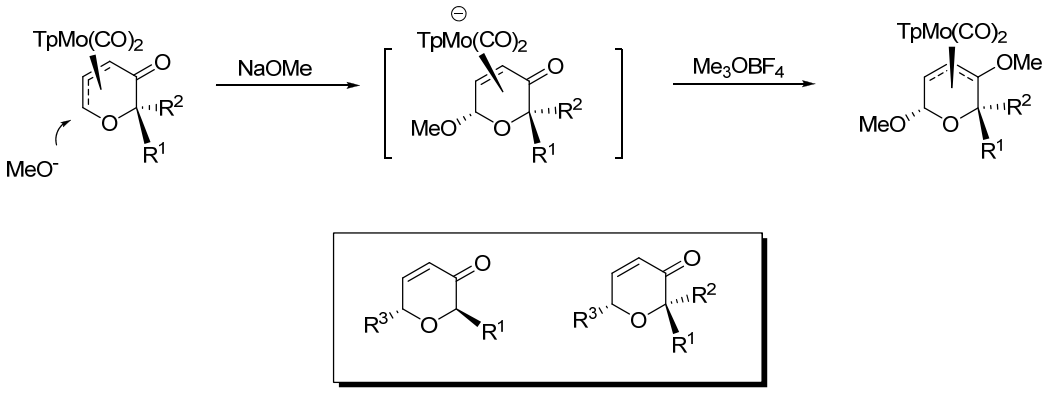
Readily available and high enantiopurity TpMo(CO)$_2$(η^3-pyranyl) and TpMo(CO)$_2$(η^3-pyridinyl) complexes have proven to be excellent enantiomeric organometallic scaffolds for the asymmetric construction of structurally diverse heterocyclic systems. This laboratory previously reported the enantiocontrolled synthesis of 2,3,6-trisubstituted dihydropyrans [84] and piperidines [85] from 2,6-dimethoxy molybdenum complexes **108** (Scheme 46) *via* a highly regioselective methoxide abstraction/nucleophilic addition sequence. During the investigation of the novel intramolecular '1,5-Michael-like' reaction,[86] it was found that neutral TpMo(CO)$_2$ (η^3-pyranyl) scaffolds also participate in an intermolecular '1,5-Michael-like' reaction with solid sodium methoxide (Scheme 47). The resulting dimethoxy complexes underwent smooth methoxide abstraction/nucleophilic addition to afford trisubstituted pyranyl complexes in good to excellent yields. The synthetic potential of this intermolecular '1,5-Michael-like' reaction of NaOMe was demonstrated by the synthesis of 2,2,6-trisubstitued pyranones and 2,6-*trans*-disubstituted pyranones.

[84] Yin, J.; Llorente, I.; Villanueva, L. A.; Liebeskind, L. S. *J. Am. Chem. Soc*. **2000**, *122*, 10458-10459.
[85] (a) Shu, C.; Alcudia, A.; Yin, J.; Liebeskind, L. S. *J. Am. Chem. Soc*. **2001**, *123*, 12477-12487. (b) Shu, C.; Liebeskind, L. S. *J. Am. Chem. Soc*. **2003**, *125*, 2878-2879.
[86] Chapter 2, Scheme 28.

Scheme 46. Synthesis of 2,3,6-Trisubstituted Dihydropyrans and Piperidines



Scheme 47. Intermolecular 1,5-Michael Reaction with NaOMe



Results and Discussion

Precursors for Intermolecular '1,5-Michael-like' Reaction

Two kinds of substrates have been investigated in the intermolecular '1,5-Michael-like' reaction: α,α-disubstituted ketone **109** and enone **110** (Figure 7).

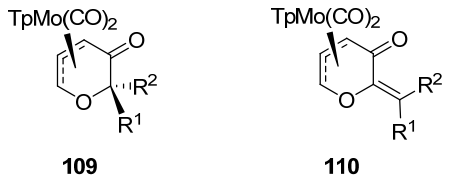
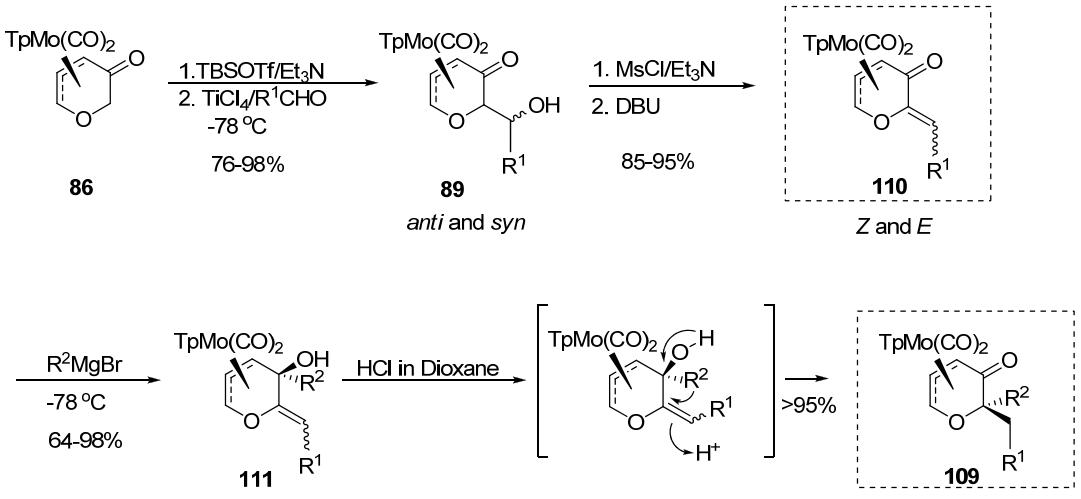


Figure 7. Substrates for Intermolecular 1,5-Michael Reaction with NaOMe

The synthetic sequence for **109** and **110** was developed by Dr. Yongqiang Zhang, and is summarized in Scheme 48.[87] First, oxopyranyl scaffold **86** was transformed into the corresponding exocyclic enones **110** (both *Z* and *E* isomers) in excellent yields through Mukaiyama-aldol reaction and mesylate elimination. Grignard reagents addition to substrate **110** gave tertiary alcohols **111** which were treated with one equivalent of HCl to induce a semipinacol rearrangement and afforded complexes **109** in almost quantitative yields with complete control of stereochemistry.

Scheme 48. Synthesis of Molybdenum Complexes 109 and 110



[87] Most complexes **109** and **110** were prepared according to Dr. Yongqiang Zhang's procedure. Detailed mechanism and procedures can be found in Dr. Yongqiang Zhang's research reports.

Intermolecular 1,5-Michael-like Reaction with NaOMe

The initial study of the intermolecular '1-5-Michael-like' reaction started with complex **109**. Figure 8 shows two possible reaction pathways for complexes **109** upon treatment with carbon nucleophiles: 1,2-addition of the carbonyl or 1,5-addition through the π-allyl unit.

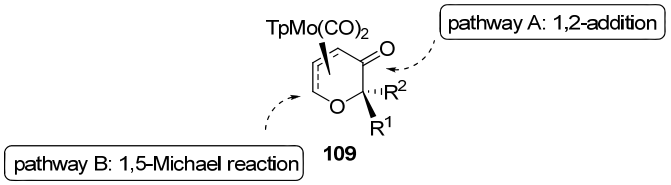
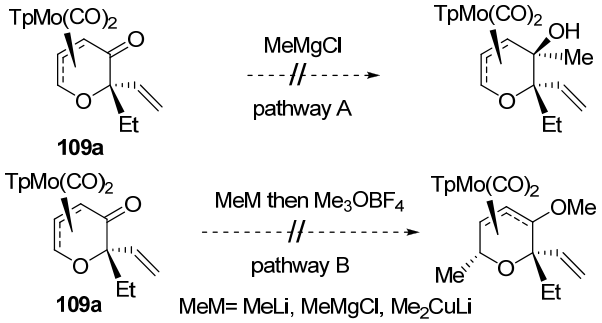


Figure 8. Possible Pathways for Nucleophilic Functionalization of 109

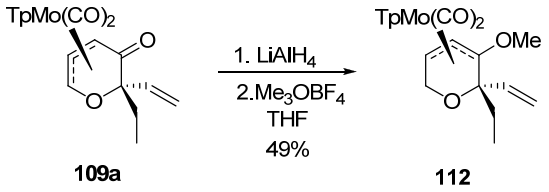
Not surprisingly, the carbonyl group in **109a** (Scheme 49) was quite robust to 1,2-addition with MeMgCl presumably due to the adjacent quaternary carbon center. This result stimulated a study of possible intermolecular '1,5-Michael-like' reactions. Different carbon nucleophiles including Grignard reagents, organolithium reagents, and organocopper reagents were explored. However, after quenching the reaction with Me_3OBF_4, no desired intermolecular '1,5-Michael' adduct was identified.

Scheme 49. Attempts of Nucleophilic Functionalization of 109a



In contrast, an intermolecular 1,5-Michael reaction was observed between a hydride ($LiAlH_4$) and **109a** (Scheme 50). The '1,5-Michael' adduct complex **112** was successfully isolated in 49% yield.

Scheme 50. Intermolecular '1,5-Michael-like' Reaction with $LiAlH_4$

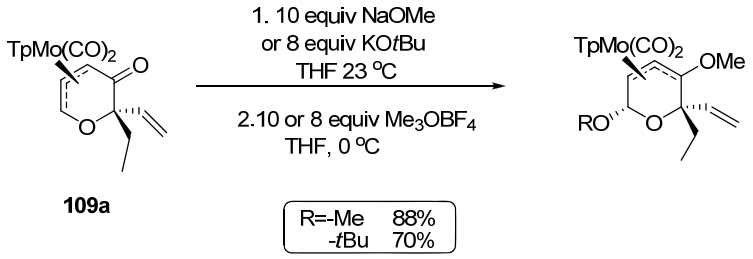


Having confirmed that neutral $TpMo(CO)_2(\eta^3$-pyranyl) complexes could be subjected to intermolecular nucleophilic functionalization, the scope of nucleophiles for this novel transformation was investigated. It was envisioned that if a methoxy group could be introduced *via* '1,5-Michael-like' reaction, sequential methoxide abstraction followed by functionalization with different carbon nucleophiles would provide rapid access to various trisubstituted pyranyl complexes.[88] With this idea in mind, the '1,5-Michael-like' reaction with solid sodium methoxide was extensively studied, and gratifyingly, methoxide was found to add to complex **109a** in THF[89] and afforded the desired intermolecular 1,5-Michael adducts after Me_3OBF_4 quench[90] (Scheme 51). In addition, other alkoxides such as KO*t*Bu were also explored and gave the '1,5-Michael' adduct in

[88] As shown in Scheme 47.
[89] No reaction was observed in CH_2Cl_2, Et_2O and TBME.
[90] Reaction temperature has to be lower to 0 °C before adding Me_3OBF_4 to prevent the cationic ring opening polymerization of THF. For reference, see: (a) Hrkach, J. S.; Matyjaszewski, K. *Macromolecules* **1990**, *23*, 4042-4046. (b) Burrows, R. C.; Crowe, B. F. *J. Appl. Poly. Sci*. **1962**, *6*, 465-473. (c) Buyle, A. M.; Matyjaszewski, K.; Penczek, St. *Macromolecules* **1977**, *10*, 269-274.

good yield.

Scheme 51. Intermolecular '1,5-Michael-like' Reaction with Alkoxides

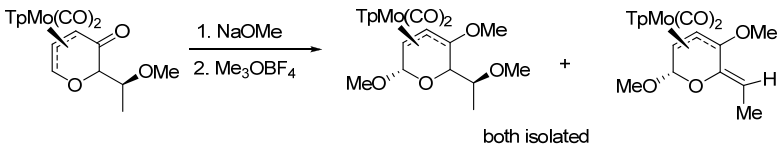


109a

The intermolecular '1,5-Michael-like' reaction proceeded smoothly with both α,α-disubstituted ketone complexes (Table 9, Entries 1-2) and enone complexes (Table 9, Entries 3-7).[91] Although complexes **113b** and **113d** (Table 9, entries 4 and 6) could be synthesized through 1,5-Michael-like reaction with NaOMe, they easily underwent partial isomerization to the corresponding *Z* isomers when taking ^{13}C NMR in $CDCl_3$.

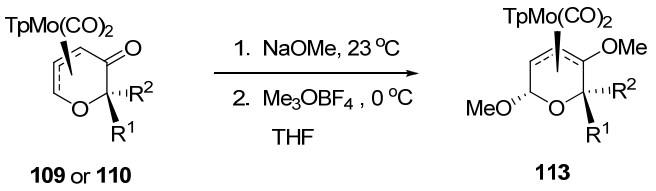
Based on the previous study of intramolecular '1,5-Michael-like' reactions,[92] the $TpMo(CO)_2$ moiety should cause complete facial selectivity in the intermolecular '1,5-Michael-like' reactions. Methoxide only approaches the terminal π-carbon from the opposite face of the bulky $TpMo(CO)_2$.

[91] Acidic α-proton at 6-Monosubstituted molybdenum complex led to other side reactions under basic conditions, thus giving low yields of 1,5-Michael reaction. For example:

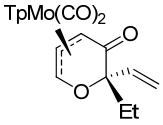
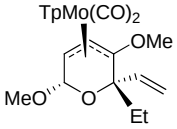
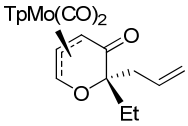
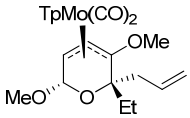
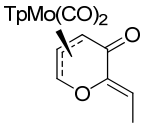
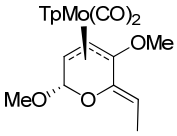
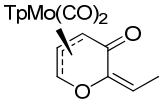
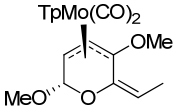
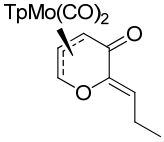
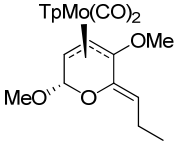
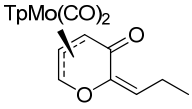
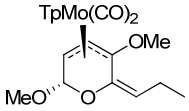
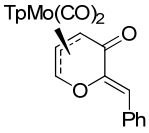
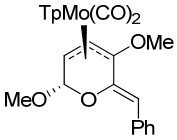


[92] Zhang, Y.; Liebeskind, L. S. *J. Am. Chem. Soc.* **2005**, *127*, 11258-11259.

Table 9. Examples of Intermolecular 1,5-Michael-Like Reaction of NaOMe



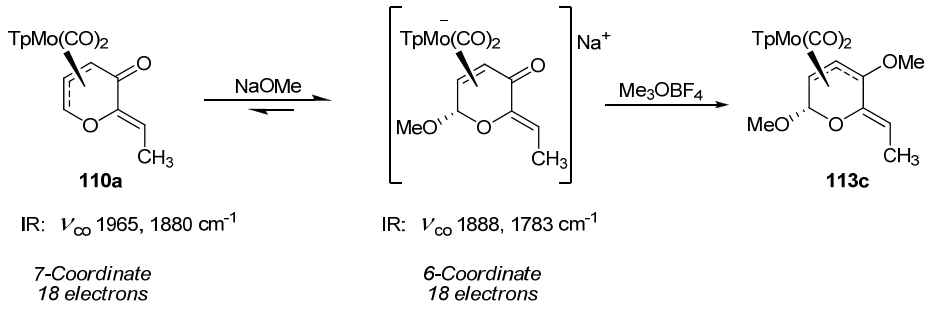
109 or **110** **113**

Entry	Substrate		Product	Yield (%)
1		**109a**		88, **113a**
2		**109b**		75, **113b**
3		**110a**		88, **113c**
4		**110b**		66, **113d**
5		**110c**		71, **113e**
6		**110d**		63, **113f**
7		**110e**		26, **113g**

Similar to the proposed mechanism for the intramolecular '1,5-Michael-like' reaction with solid NaOMe described in Chapter 2, Scheme 32, an anionic η^2-molybdenum

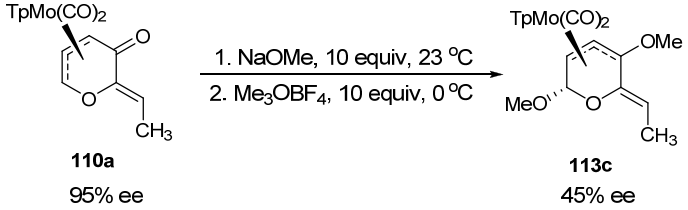
intermediate was proposed to be involved in the intermolecular '1,5-Michael-like' reaction with NaOMe (Scheme 52). The infrared analysis of the reaction mixture of **100a** and NaOMe revealed that two metal carbonyl[93] shifted from 1965 and 1880 cm^{-1} (complex **110a**) to 1888 and 1783 cm^{-1} (the reaction mixture), which suggests the reaction intermediatan possesses an electron rich metal center.

Scheme 52. Proposed Mechanism for Intermolecular '1,5-Michael-Like' Reaction with NaOMe[93]



During the investigation of enantiocontrolled '1,5-Michael-like' reaction of (-)-**110a** with NaOMe under standard conditions, partial racemization was observed (Scheme 53).

Scheme 53. Observed Racemization of Intermolecular 1,5-Michael Reaction of 110a

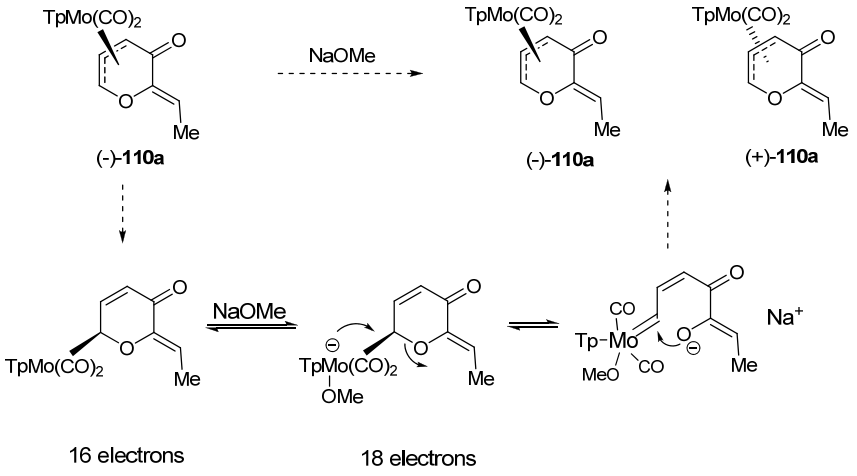


This racemization might come from the racemization of the starting enone (-)-**110a**

[93] Lee, M. D., IV, Ph.D. thesis, Emory University, 2008.

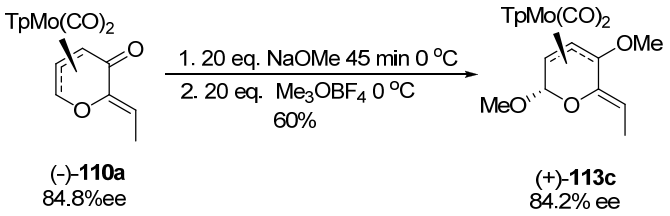
(Scheme 54). Under 1,5-Michael conditions, $TpMo(CO)_2$ moiety in enone (-)-**110a** could slip from a η^3-complex to a η^1-complex. Then excessive methoxide in the reaction mixture would facilitate the ring-opening of pyran ring and form a metal carbene species. Upon subsequent ring-closure, $TpMo(CO)_2$ could reside at both enantiotropic faces of the pyran ring, thus causing the racemization of (-)-**110a**.

Scheme 54. Proposed Racemization Mechanism for Intermolecular 1,5-Michael Reaction of (-)-110a

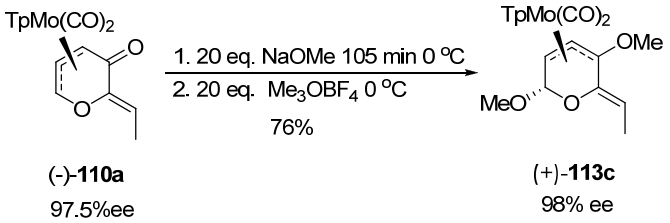


To suppress the undesired racemization, we lowered the reaction temperature and shortened the reaction time of the first step (addition of methoxide) to avoid the undesired ring-opening of **110a**. Reaction of (-)-**110a** with 20 equiv NaOMe in 45 min at 0 ^oC afforded (+)-**113c** in 60% yield with almost no enantiopurity loss (Scheme 55). Later, after optimization, Maurice Lee demonstrated that 97.5% ee (-)-**110a** could be converted to (+)-**113c** in 76% yield and 98% ee (Scheme 56) in which higher reaction concentrations increased the reaction yield significantly.

Scheme 55. Optimized Condition for Enantiocontrolled '1,5-Michael' Reaction



Scheme 56. Enantiocontrolled '1,5-Michael' Reaction with NaOMe[94]



Synthetic Application of Intermolecular '1,5-Michael-like Reaction' of NaOMe

Dimethoxy molybdenum complexes **113a-g** (Table 9) enable further functionalization of the pyranyl molybdenum scaffolds *via* the previously established methoxide abstraction/nucleophilic addition sequence. This strategy was successfully applied to the synthesis of 2,2,6-trisubstituted pyranones and 2,6-*trans*-disubstitued pyranones.

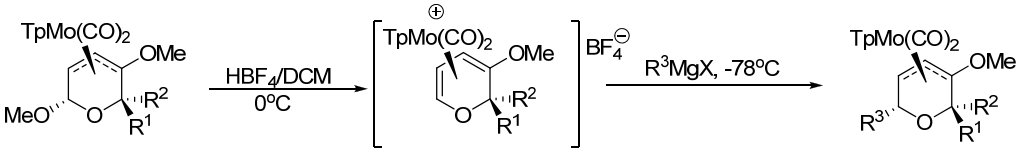
Synthesis of 2,2,6-trisubstitued Pyranones

Conversion of the 2-methoxy molybdenum complexes **113a** and **113b** to the corresponding 2,2,6-trisubstituted complexes was accomplished by ionization of methoxy group with HBF_4. This was followed by the addition of carbon nucleophiles at -78 °C. This sequence is illustrated in Scheme 57, and the yields of trisubstituted molybdenum

[94] Lee, M. D., IV, Ph.D. thesis, Emory University, 2008.

complexes are listed in Table 10. In this process, the formation of cationic dienes **115** was very efficient and smooth. Different carbon nucleophiles selectively added to the carbon adjacent to the pyranyl oxygen from the opposite face of bulky $TpMo(CO)_2$, and furnished various 2,2,6-trisubstituted molybdenum complexes **114** in good to excellent yields with complete regio- and stereoselectivity.

Scheme 57. Synthesis of 2,2,6-Trisubstituted Molybdenum Complexes



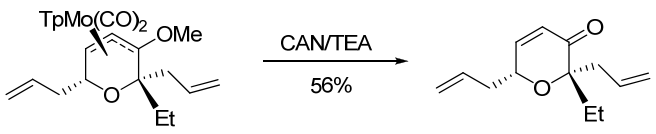
113 **115** **114**

Table 10. Synthesis of 2,2,6-Trisubstituted Pyranyl Molybdenum Complexes

Entry	Substrate	R^1	R^2	R^3M	Yield (%)
1	**113a**	Et	vinyl	MeMgCl	83, **114a**
2	**113a**	Et	vinyl	VinylMgCl	90, **114b**
3	**113a**	Et	vinyl	PhenylMgCl	94, **114c**
4	**113b**	Et	allyl	*i*PrMgCl	65, **114d**
5	**113b**	Et	allyl	AllylMgCl	82, **114e**
6	**113b**	Et	allyl	lithium phenylacetylide	74, **114f**

Oxidative demetalation of trisubstituted molybdenum complexes **114** with ceric ammonium nitrate should provide the 2,2,6-trisubstituted pyranones. In fact, complex **114e** was decomplexed to afford (2*S*,6*R*)-2,6-dially-2-ethyl-2*H*-pyranone **116** in 56% yield (Scheme 58).

Scheme 58. Synthesis of (2*S*, 6*R*)-2,6-Dially-2-Ethyl-2*H*-Pyranone 116



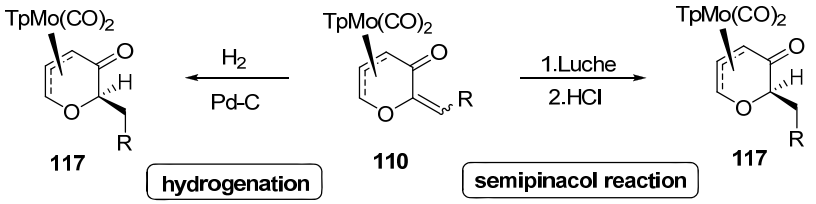
114e **116**

Synthesis of 2,6-trans disubstituted pyranones

Traditionally, organometallic scaffolds are functionalized by conversion of a neutral allylmolybdenum to either a cationic η^4-diene or by CO→NO^+ exchange to generate a cationic η^3-allylmolybdenum complex. Subsequent reaction with a nucleophile takes place from the opposite face to the TpMo moiety. As a result, when multiple substituents are introduced, they necessarily end up oriented *cis* to each other. Therefore, how to fully control the relative stereochemistry of enantiomeric scaffolds, and deliver two substituents *trans* to each other on the enantiomeric scaffolds remains a challenge in our enantiomeric scaffolding approach.

Two general methods have been successfully developed in our lab to introduce a substituent *syn* to the $TpMo(CO)_2$ unit from enone **110** (Scheme 59): catalytic hydrogenation and 1,2-Luche reduction of the carbonyl followed by a stereospecific semipinacol reaction.

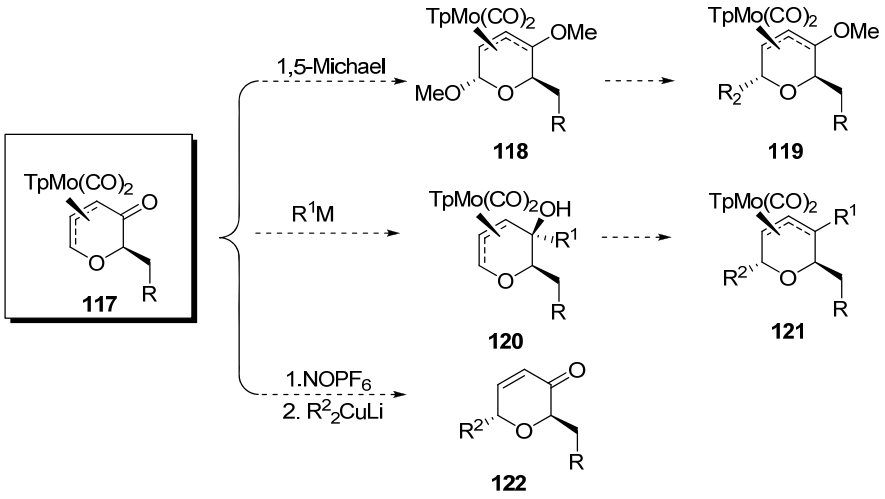
Scheme 59. Methods to *syn*-Substituents



Starting from complex **117**, three routes were designed to access the 2,6-*trans*-disubstituted molybdenum complexes (Scheme 60). First, intermolecular 1,5-Michael reaction of **117** with NaOMe would provide dimethoxy complex **118** which could undergo methoxy abstraction with HBF_4 and sequential nucleophile addition to afford 2,6-*trans*-disubstituted molybdenum complexes **119**. Second, 1,2-addition of the carbonyl in **117** will give tertiary alcohol **120** which might be transformed to 2,6-*trans*-disubstituted molybdenum complex **121** *via* hydroxyl abstraction with $TrPF_6$ followed by addition of nucleophiles. Finally, ligand exchange with NO^+ could provide a cationic η^3-allylmolybdenum complexes, subsequent reaction with a nucleophile might provide 2,6-*trans*-disubstituted pyranone **122**.[95]

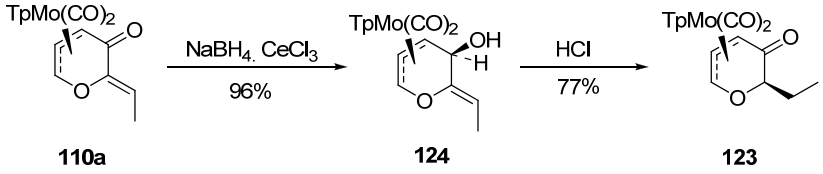
[95] This method has not been studied so far.

Scheme 60. Proposed Synthesis of 2,6-*trans*-Disubstituted Molybdenum Complexes from 117



To investigate the strategies described above, substrate **123** (Scheme 61) was synthesized first from enone **110a** by Luche reduction followed by HCl induced 1,2-hydride migration (semipinacol reaction).

Scheme 61. Synthesis of Complex 123 *via* Semipinacol Reaction

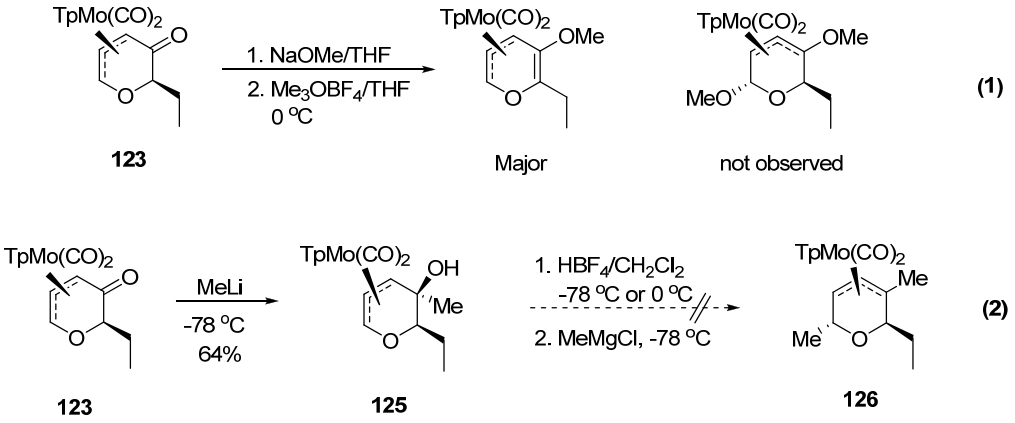


However, intermolecular 1,5-Michael reaction of NaOMe with **123** only led to the methylation of the ketone enolate (Scheme 62, eq 1). Treatment of **123** with MeLi[96] generated **126** in 64% yield (Scheme 62, eq 2). Upon treatment of HBF_4, the reaction

[96] No reaction was observed with MeMgCl.

changed from orange to purple immediately,[97] but complex **126** was not observed after addition of methyl magnesium chloride.

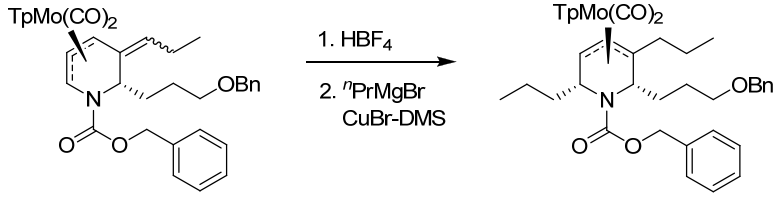
Scheme 62. Attempts to Synthesize 2,6-*trans*-Substituted Pyranyl Complexes from Substrate 123



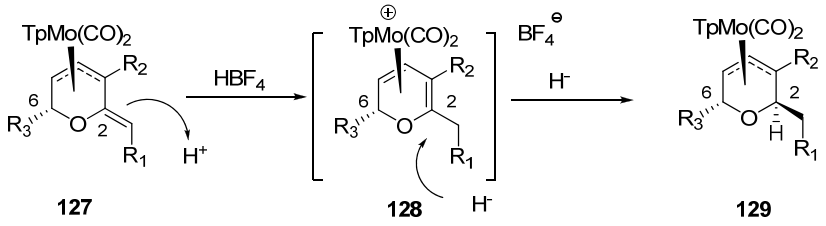
Inspired by the protonation/nucleophilic addition strategy developed by Dr. Heilam Wong in the synthesis of trisubstituted tetrahydropyridinyl molybdenum complexes[98] (Scheme 63), a protonation/hydride addition approach was proposed to prepare 2,6-*trans*-disubstituted pyranyl molybdenum complexes (Scheme 64). If alkylidene **127** can be synthesized, then protonation of the exocyclic double bond would generate a molybdenum stabilized cationic diene **128**. Subsequent delivery of a hydride should occur regiospecifically at the carbon adjacent to the pyranyl oxygen from the opposite face the bulky $TpMo(CO)_2$ unit. As a result, the substituent at C-2 would be 'pushed' *syn* to the TpMo $(CO)_2$ and *trans* to the substituent at C-6.

[97] Purple color might indicate decomposition of the reaction mixture.
[98] Wong, H., Ph.D. thesis, Emory University, 2006.

Scheme 63. Protonation/Nucleophilic Addition Strategy in the Synthesis of Trisubstituted Pyridinyl Molybdenum Complexes



Scheme 64. Proposed Synthetic Route to 2,6-*trans*-Substituted Pyranyl Molybdenum Complexes from Alkylidene 127

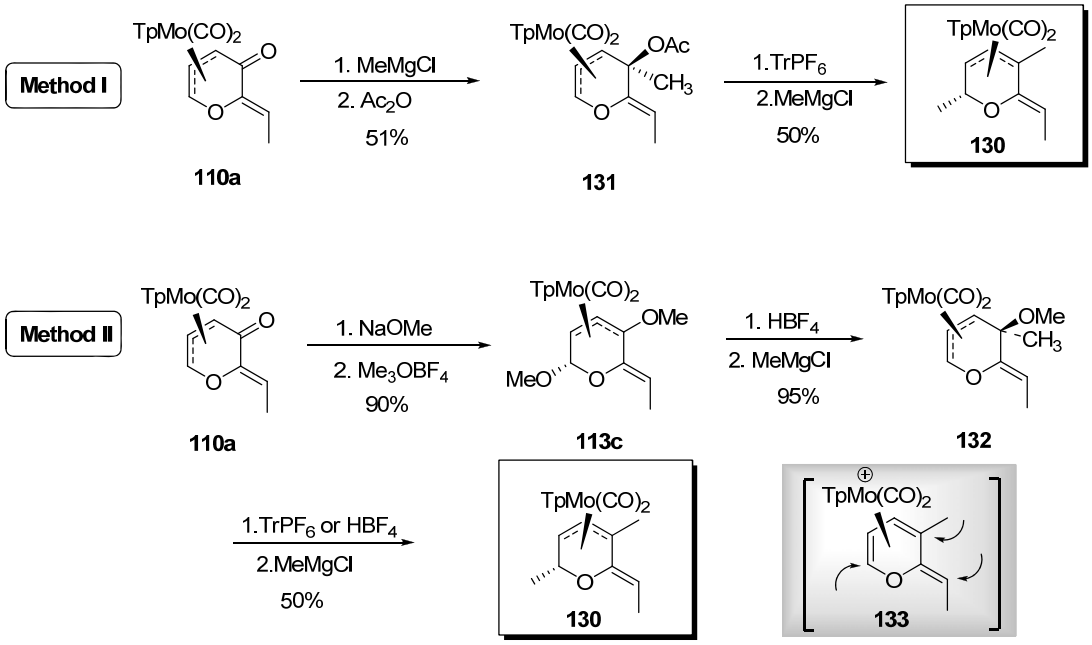


To test this protonation/hydride addition strategy, alkylidene **130** was prepared *via* two different methods as depicted in Scheme 65. First, addition of methyl magnesium chloride to enone **110a** followed by immediate acetylation of the alkoxide afforded complex **131** in 51% yield.[99] Acetoxy abstraction with $TrPF_6$ and subsequent addition of methyl magnesium chloride gave complex **130** in 50% yield. Complex **130** can also be prepared through intramolecular '1,5-Michael reaction' of enone **110a** with NaOMe. Methoxide abstraction of the 1,5-Michael adduct **113c** followed by addition of methyl magnesium chloride provided **132** in 95% yield. Compound **132** was coverted to alkylidene **130** in 50% yield by another methoxide abstraction and subsequent addition of

[99] The low yields presumably came from the acetylation since the produced alkoxide was blocked by the bulky $TpMo(CO)_2$.

methyl magnesium chloride. The low yields of the last step of both methods can be explained by their common reaction intermediate cationic diene **133**. Diene **133** has three competitive addition sites which might affect the regioselectivity and lead to the low yields.[100]

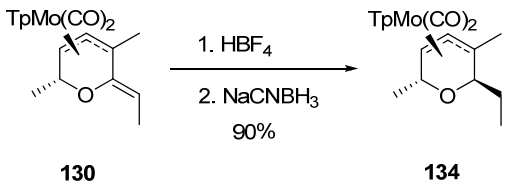
Scheme 65. Synthesis of Alkylidene 130



The protonation/hydride addition strategy was proven very efficient for alkylidene **130** (Scheme 66). Protonation of the electron-rich exocyclic double bond in complex **130** with HBF_4 followed by addition of $NaCNBH_3$ furnished the desired 2,6-*trans* substituted complexes **134** in 90% yield.

[100] There were minor products in both reactions. However, they were not identified. For further studies on the methoxy abstraction/nucleophilic addition reaction of complex **113** and **132**, see: Lee, M. D., IV, Ph.D. thesis, Emory University, 2008.

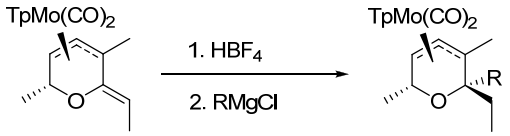
Scheme 66. Synthesis of 2,6-*trans*-Sbustituted Molybdenum Complex 134



130 **134**

Meanwhile, two different Grignard reagents were also found to effectively react with the generated cationic η^4-diene regiospecifically at C-2 to generate a quaternary carbon center (Scheme 67).[101]

Scheme 67. Protonation/Carbanoin Addition to Tetrasubstituted Pyranyl Molybdenum Complexes

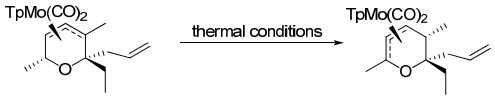


130

R = Me, **135** 64%
Allyl, **136** 67%

Unfortunately, attempts to expand the scope of alkylidene complexes *via* the second method shown in Scheme 65 using various carbon nucleophiles other than methyl Grignard reagent encountered complicated regioselectivity[102] (Scheme 68). Maurice Lee systematically studied the regioselectivity of methoxy abstraction/nucleophilic addition sequence of complex **113c** with different nucleophiles. Some trends were observed and

[101] Tetrasubstituted **136** is not stable. It underwent partial thermal rearrangement to form complex **137** on a rotary evaporator.

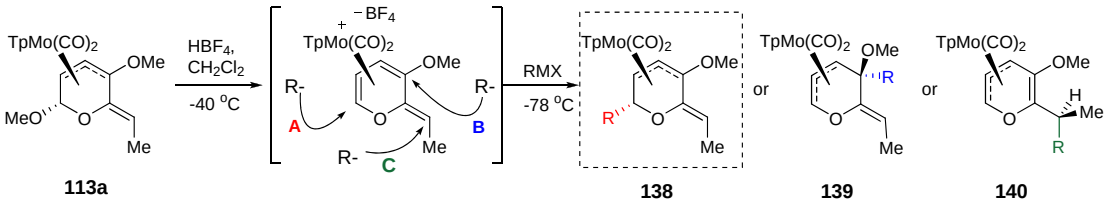


136 **137**

[102] For details, see: Lee, M. D., IV, Ph.D. thesis, Emory University, 2008.

summarized by Maurice Lee as shown in Scheme 68, but the reason is still not fully understood.

Scheme 68. Regioselectivity of Various Nucleophiles[103]



A : R=aryl Grignards only

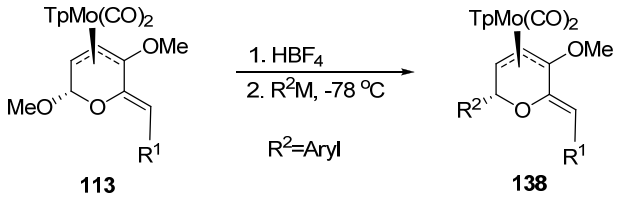
B : R= Grignard reagents with sp^3-hybridized substituents and organolithium reagents

C : R= organocuprate and *t*BuMgCl

Among the substrates listed in Scheme 68, alkylidene **138** can be directly subjected to the protonation/hydride addition sequence without further manipulation. Therefore, the synthetic study of 2,6-*trans*-disubstituted molybdenum complexes started with preparation complex **138**. Conversion of dimethoxy complexes **113** to alkylidenes **138** proceeded smoothly with moderate yields as shown in Table 11. Aryl anions added to C-6 regiospecifically as described in Scheme 68 (path A).

[103] Lee, M. D., IV, Ph.D. thesis, Emory University, 2008.

Table 11. Synthesis of Alkylidene 138

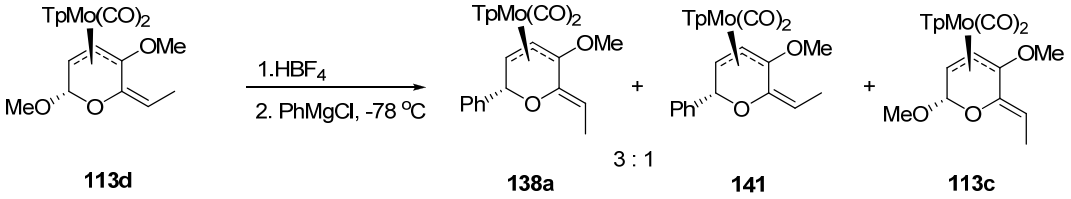


113 138

Entry	R^1	R^2	Yield (%)
1	Me, **113c**	Ph	56, **138a**
2	Et, **113e**	(*m*-OMe)Phenyl	81, **138b**
3	Ph, **113g**	2-mesityl	62, **138c**

It should be mentioned dimethoxy *Z*-alkylidenes are better substrates for protonation/hydride addition reaction since *E*-alkylidenes are easily isomerized to their *Z* analogs under protonation/nucleophilic addition conditions. For example, upon treatment of HBF_4 and PhMgCl, *E*-alkylidene **113d** was converted to **138a**, **141** and *Z*-alkylidene **113c** (all isolated) (Scheme 69).

Scheme 69. Isomerization of 113d under Protonation/Nucleophilic Addition Condition

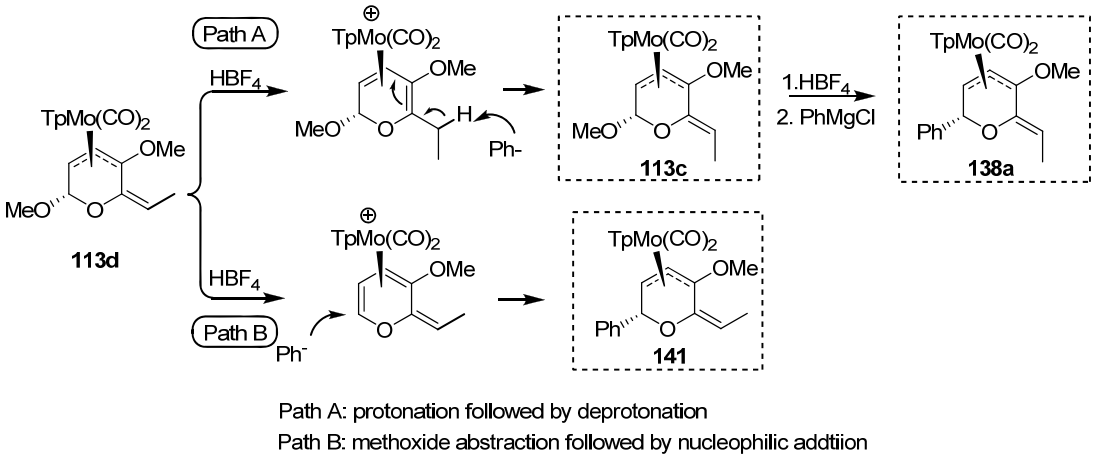


113d 138a 141 113c

This result can be rationalized by the competition between methoxide abstraction and protonation of the exocyclic double bond in **113d** (Scheme 70). Protonation of the **113d** followed by deprotonation with PhMgCl afforded the more stable dimethoxy complex **113c** which could lead to the formation of complex **138a** (Scheme 70, path A), whereas

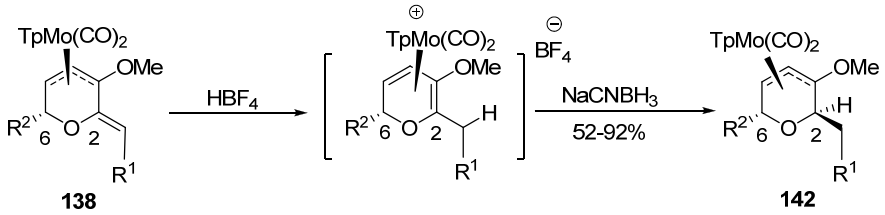
methoxide abstraction of **113d** and subsequent addition of phenyl magnesium chloride afforded *E*-alkylidene **141** (Scheme 70, path B).

Scheme 70. Proposed Mechanism for the Isomerization of 113d



Finally, the protonation/hydride addition reaction converted substrates **138** to 2,6-*trans* substituted complexes **142** smoothly in 52% to 92% yields (Table 12).

Table 12. Synthesis of 2,6-*trans*-Substituted Molybdenum Complexes



Entry	Substrate	R^1	R^2	Yield (%)
1	**138a**	Me	Ph	92, **142a**
2	**138b**	Et	(*m*-OMe)Phenyl	83, **142b**
3	**138c**	Ph	2-mesityl	85, **142c**

Single X-ray crystallographic analysis of (±)-**142a** (Figure 9) confirmed its structure: (1)

phenyl and ethyl group are *trans* to each other; (2) ethyl group is *syn* to $TpMo(CO)_2$. As a result, our hypothesis was also proved: the hydride addition proceeded from the opposite face of $TpMo(CO)_2$ unit and regiospecifically at C-2.

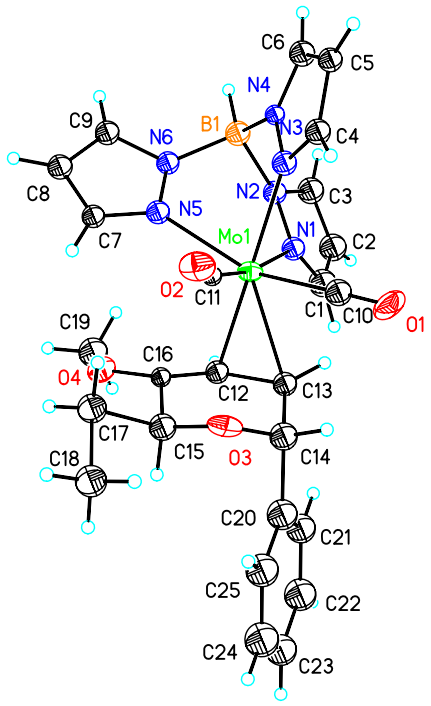
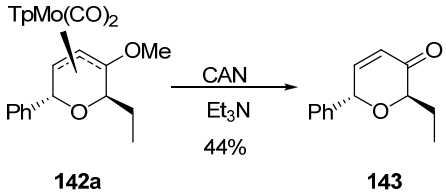


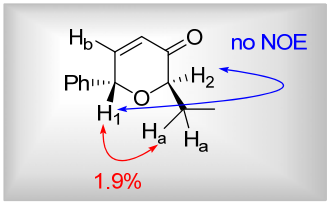
Figure 9. ORTEP View of Complex (±)-142a

The synthetic potential of this methodology was tested by demetalation of **142a** with CAN to afford *trans*-2-ethyl-6-phenyl dihydropyranone **143**[104] in 44% yield (Scheme 71). The relative stereochemistry in **143** is unambiguously established by NOE measurements.

[104] Then enantiocontrolled synthesis of **(-)-143** has been completed by Lee, M. D., IV.

Scheme 71. Synthesis of (2*R*,6*S*)-2-Ethyl-6-Phenyl-Pyranone 143



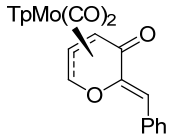


Conclusion

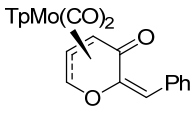
Solid sodium methoxide can undergo efficient intermolecular '1,5-Michael-like' reaction with neutral $TpMo(CO)_2$(5-oxo-η^3-pyranyl) complexes with complete regio- and stereocontrol. Ionization of the methoxy group with HBF_4 followed by carbon nucleophiles addition affords 2,2,6-trisubstituted and 2,6-*trans* disubstituted pyranyl molybdenum complexes in good to excellent yields. The potential of this novel transformation was demonstrated by the synthesis of 2,2,6-trisubstitued pyranone **116** and 2,6-*trans*-disubstitued pyranone **143**.

Experimental Section

*Molybdenum complexes **109a**, **109b**, **110a**, **110b**, **110c**, **110d** were prepared according to Dr. Yongqiang Zhang's procedure.*[105]



(±)-*Z*-**110e**



(±)-*E*-**110e**

(±)-Dicarbonyl[hydridotris(1-pyrazolyl)borato][(2*S*)-η-(2,3,4)-6-(*Z*)-benzylidene)-5-oxo-5,6-dihydro-2*H*-pyran-2-yl]molybdenum, (±)-*Z*-110e.

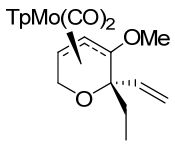
To a solution of *anti*-**89d** (175 mg, 0.31 mmol, 1 equiv) in CH_2Cl_2 (10 mL) was added DMAP (18.8 mg, 0.15 mmol, 0.5 equiv), Et_3N (647 μL, 0.46 mmol, 1.5 equiv), and methanesulfonyl chloride (31 μL, 0.40 mmol, 1.3 equiv). The reaction mixture was stirred 10 min at room temperature. TLC monitoring the reaction indicated the disappearance of the starting material and formation of the mesylated product. The solution was passed through a short pad of silica gel (50% EtOAc in hexanes). The solvents were completely removed on a rotary evaporator, and the residue was dissolved in CH_2Cl_2 (5 mL). The solution was cooled down to 0 ºC and DBU (69 μL, 0.46 mmol, 1.5 equiv) was slowly added via syringe. The reaction mixture was stirred for 45 min at room temperature. The solution was again passed through a short pad of silica gel, concentrated, and purified by column chromatography on silica gel (hexane-EtOAc 1:1)

[105] Dr. Yongqiang Zhang, Liebeskind's group final research report, p 27-36, Emory University.

to afford the minor isomer (±)-*E*-**110e** (3 mg, 2%) and the major isomer (±)-*Z*-**110e** (160 mg, 94%) as yellow solid.

(±)-*E*-**110e**: TLC (R_f = 0.58, hexanes-EtOAc 1:1). ^{1}H NMR (600 MHz, $CDCl_3$): δ 8.52 (d, *J* = 1.2 Hz, 1H), 7.93 (d, *J* = 1.2 Hz, 1H), 7.67 (d, *J* = 2.4 Hz, 1H), 7.62 (m, 3H), 7.60 (d, *J* = 1.8 Hz, 1H), 7.52 (d, *J* = 2.4 Hz, 1H), 7.30-7.24 (m, 4H), 6.34 (s, 1H), 6.32 (t, *J* = 2.4 Hz, 1H), 6.28 (t, *J* = 2.1 Hz, 1H), 6.22 (t, *J* = 2.4 Hz, 1H), 4.95 (dd, *J* = 6.6, 1.8 Hz, 1H), 4.33 (dd, *J* = 6.3, 4.5 Hz, 1H). HRMS (ESI) Calcd for $C_{23}H_{20}BMoN_6O_4$ ($[M+H]^+$): 553.0688. Found: 553.0689.

(±)-*Z*-**110e**: TLC (R_f = 0.53, hexanes-EtOAc 1:1). ^{1}H NMR (600 MHz, $CDCl_3$): δ 8.53 (d, *J* = 1.8 Hz, 1H), 7.98 (d, *J* = 1.8 Hz, 1H), 7.75 (s, 2H), 7.74 (s, 1H), 7.67 (d, *J* = 2.4 Hz, 1H), 7.64 (d, *J* = 1.8 Hz, 1H), 7.55 (d, *J* = 2.4 Hz, 1H), 7.40 (dd, *J* = 4.8, 2.4 Hz, 1H), 7.55 (t, *J* = 7.5 Hz, 2H), 7.28 (m, 1H), 6.83 (s, 1H), 6.32 (m, 2H), 6.25 (t, *J* = 1.8 Hz, 1H), 5.06 (dd, *J* = 6.6, 2.4 Hz, 1H), 5.11 (d, *J* = 6.6, 4.8 Hz, 1H). ^{13}C NMR (150 MHz, $CDCl_3$): δ 223.8, 222.1, 181.1, 147.2, 143.4, 143.1, 141.3, 136.3, 136.2, 134.6, 133.8, 130.1 (2C), 128.2 (2C), 127.7, 111.7, 108.3, 106.2, 105.9, 105.6, 102.9, 71.8, 66.4. HRMS (ESI) Calcd for $C_{23}H_{20}BMoN_6O_4$ ($[M+H]^+$): 553.0688. Found: 553.0689.



112

(±)-Dicarbonyl[hydridotris(1-pyrazolyl)borato][(2*S*,3*R*)-η-(3.4.5)-2-ethyl-3-

methoxy-6-vinyl-3,6-dihydro-2*H*-pyran-3-yl]molybdenum, (±)-112.

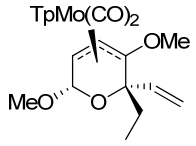
To a Schlenk flask charged with a solution of **109a** (23 mg, 0.044 mmol, 1 equiv.) in THF (2 mL) was added $LiAlH_4$ (1.0 M in THF, 44 μL, 0.044 mmol, 1 equiv) at 0 ºC. The reaction mixture was stirred at that temperature for 5 min, and then quenched with Me_3OBF_4 (13mg, 0.088 mmol, 2 equiv.). After being stirred at room temperature for 40 min, the reaction was diluted with CH_2Cl_2, and then passed through a short pad of silica gel. The solvents were completely removed on a rotary evaporator, and the residue was further purified by column chromatography on silica gel (hexanes-EtOAc 3:1) to afford an orange solid product 11**2** (11 mg, 49%).

(±)-11**2**: TLC (R_f = 0.87, hexanes-EtOAc 2:1). ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.32 (d, *J* = 2.0 Hz, 1H), 7.80 (d, *J* = 2.0 Hz, 1H), 7.65 (d, *J* = 2.0 Hz, 1H), 7.60 (d, *J* = 2.0 Hz, 1H), 7.50 (d, *J* = 2.4 Hz, 1H), 7.43 (d, *J* = 2.0 Hz, 1H), 6.20 (m, 3H), 5.84 (dd, *J* = 17.2, 11.2 Hz, 1H), 5.25 (m, 2H), 4.13 (dd, *J* = 12.4, 1.60 Hz, 1H), 3.91 (d, *J* = 8.0 Hz, 1H), 3.75 (dd, *J* = 12.4, 0.8 Hz, 1H), 3.69 (d, *J* = 8.4 Hz, 1H), 2.68 (s, 3H), 2.10-2.45 (m, 2H), 0.90 (t, *J* = 7.6 Hz, 3H).

General procedure for intermolecular 1,5-Michael-like reaction of NaOMe.

To a solution of molybdenum complex **109** or **110** (1 equiv) in dry THF was added solid NaOMe (10 equiv) under argon. After being stirred at room temperature for 3.5 to 5 hours, the reaction was cooled to 0 ºC. To the reaction mixture was added solid Me_3OBF_4 (10 equiv). Then the reaction was stirred at 0 ºC from 40 min to 1 hour after which TLC

indicated the formation of a new compound. The reaction was quenched by adding Et_3N at 0 ºC. The cold solution was directly passed through a short silica gel column (pre-neutralized by 5% Et_3N) with Et_2O. The solvents were completely removed on a rotary evaporator, and the residue was further purified by column chromatography on silica gel neutralized with 5% Et_3N.



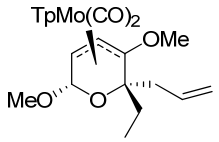
113a

(±)-Dicarbonyl[hydridotris(1-pyrazolyl)borato][(2*S*,3*R*,6*S*)-η-(3.4.5)-2,5-dimethoxy-6-ethyl-6-vinyl-3,6-dihydro-2*H*-pyran-3-yl]molybdenum, (±)-113a.

Following the *general procedure,* **109a** (150 mg, 0.29 mmol, 1 equiv) was dissolved in THF (20 mL), and reacted with NaOMe (165 mg, 3.0 mmol, 10 equiv) for 5 h followed by adding solid Me_3OBF_4 (480 mg, 3.2 mmol, 11 equiv). Purification by column chromatography on silica gel (hexanes-EtOAc 4:1) afforded **113a** (140 mg, 88%) as a dark orange solid.

(±)-**113a**: TLC (R_f = 0.62, hexanes-EtOAc 3:1). IR (cm^{-1}): 2937 (m), 2482 (m), 1926 (s), 1826 (s), 1505(s), 1305 (s), 1227 (s). ^1H NMR (600 MHz, $CDCl_3$): δ 8.27 (d, *J* = 1.8 Hz, 1H), 7.76 (d, *J* = 1.8 Hz, 1H), 7.66 (d, *J* = 2.4 Hz, 1H), 7.60 (d, *J* = 1.8 Hz, 1H), 7.50 (d, *J* = 2.4 Hz, 1H), 7.45 (d, *J* = 1.8 Hz, 1H), 6.29 (dd, *J* = 17.4, 10.8 Hz, 1H), 6.20 (m, 3H), 5.21 (d, *J* = 18.0 Hz, 1H), 5.11 (d, *J* = 10.8 Hz, 1H), 4.83 (s, 1H), 4.10 (d, *J* = 7.8 Hz,

1H), 3.77 (d, *J* = 7.2 Hz, 1H), 3.45 (s, 3H), 2.63 (s, 3H), 2.31-2.43 (m, 2H), 0.99 (t, *J* = 7.8 Hz, 3H). ^{13}C NMR (150 MHz, $CDCl_3$): δ 232.9, 228.3, 146.8, 146.0, 145.3, 143.6, 139.3, 136.2, 135.4, 134.7, 113.4, 105.6, 105.6, 105.5, 101.1, 78.1, 61.7, 55.4, 54.0, 53.6, 28.4, 7.2. HRMS (ESI) Calcd for $C_{22}H_{27}BMoN_6O_5$ ($[M]^+$): 564.1185. Found: 564.1187.



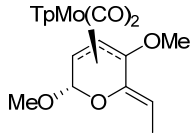
113b

(±)-Dicarbonyl[hydridotris(1-pyrazolyl)borato][(2*S*,3*R*,6*S*)-*η*-(3.4.5)-6-allyl-2,5-dimethoxy-6-ethyl-3,6-dihydro-2*H*-pyran-3-yl]molybdenum, (±)-113b.

Following the *general procedure,* **109b** (80 mg, 0.15 mmol, 1 equiv) was dissolved in THF (10 mL), and reacted with NaOMe (86 mg, 1.50 mmol, 10 equiv.) for 4.5 h followed by adding solid Me_3OBF_4 (223 mg, 1.50 mmol, 10 equiv). Purification by column chromatography on silica gel (hexanes-EtOAc 3:1) afforded (±)-**113b** (65 mg, 75%) as a dark orange solid.

(±)-**113b**: TLC (R_f = 0.67, hexanes-EtOAc 3:1). IR (cm^{-1}): 2937 (m), 2482 (m), 1926 (s), 1826 (s), 1517(m), 1409(s), 1305 (s), 1224 (s), 1119 (s). ^{1}H NMR (600 MHz, $CDCl_3$): δ 8.25 (d, *J* = 1.8 Hz, 1H), 7.71 (d, *J* = 1.8 Hz, 1H), 7.65 (d, *J*= 1.8 Hz, 1H), 7.59 (d, *J* = 1.8 Hz, 1H), 7.50 (d, *J* = 1.8 Hz, 1H), 7.45 (d, *J* = 2.4 Hz, 1H), 6.19 (m, 3H), 5.96 (m, 1H), 5.04 (dd, *J* = 17.1, 2.1 Hz, 1H), 4.96 (dd, *J* = 10.4, 2.1 Hz, 1H), 4.82 (s, 1H), 4.09 (d, *J* = 8.4 Hz, 1H), 3.71 (d, *J* = 7.8 Hz, 1H), 3.45 (s, 3H), 2.85 (d, *J* = 8.6 Hz, 2H), 2.55 (s,

3H), 2.29 (m, 2H), 1.03 (t, J = 7.2 Hz, 3H). ^{13}C NMR (150 MHz, $CDCl_3$): δ 233.1, 228.4, 151.1, 146.0, 145.2, 139.3, 136.1, 135.3, 135.3 134.7, 115.7, 105.61, 105.59, 105.57, 101.1, 78.1, 60.9, 55.6, 54.0, 52.6, 46.6, 27.2, 7.0. HRMS (ESI) Calcd for $C_{23}H_{26}BMoN_6O_4$ ([M-OMe]$^+$): 547.1157. Found: 547.1169.



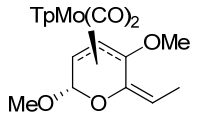
113c

(±)-Dicarbonyl[hydridotris(1-pyrazolyl)borato][(2*S*,3*R*)-η-(3,4,5)-6-(*Z*)-ethylidene-2,5-dimethoxy-3,6-dihydro-2*H*-pyran-3-yl]molybdenum, (±)-113c.

Following the *general procedure,* **110a** (50 mg, 0.102 mmol, 1 equiv) was dissolved in THF (3 mL), and reacted with NaOMe (55 mg, 1.02 mmol, 10 equiv) for 3.5 h followed by adding solid Me_3OBF_4 (150mg, 1.02 mmol, 10 equiv). Purification by column chromatography on silica gel (hexanes-EtOAc 2:1) afforded (±)-**113c** (48 mg, 88%) as a brown solid.

(±)-**113c**: TLC (R_f = 0.53, hexanes-EtOAc 2:1). IR (cm^{-1}): 2930 (w), 2482 (w), 1926 (s), 1841 (s), 1505 (s), 1409 (s), 1305(s), 1239 (s). ^{1}H NMR (600 MHz, $CDCl_3$): δ 8.30 (d, J = 2.4 Hz, 1H), 7.69 (d, J = 2.4 Hz, 1H), 7.65 (d, J = 1.8 Hz, 1H), 7.62 (d, J = 2.4 Hz, 1H), 7.58 (d, J = 1.8 Hz, 1H), 7.49 (d, J = 1.8 Hz, 1H), 6.21 (t, J = 2.1 Hz, 1H), 6.20 (t, J = 2.1 Hz, 1H), 6.17 (t, J = 2.1 Hz, 1H), 5.62 (q, J = 7.2 Hz, 1H), 4.98 (s, 1H), 4.11 (d, J = 7.8 Hz, 1H), 3.76 (d, J = 8.4 Hz, 1H), 3.49 (s, 3H), 3.01 (s, 3H), 1.81 (t, J = 7.2 Hz, 3H).

^{13}C NMR (150 MHz, $CDCl_3$): δ 232.1, 227.5, 146.6, 144.0, 142.2, 139.4, 136.3, 135.7, 134.6, 134.6, 105.6, 105.5, 105.4, 105.2, 99.8, 57.4, 56.1, 54.9, 52.4, 10.0. HRMS (ESI) Calcd for $C_{20}H_{23}BMoN_6O_5$ ($[M]^+$): 536.0872. Found: 536.0870.



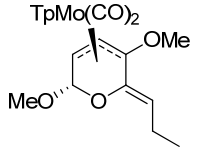
113d

(±)-Dicarbonyl[hydridotris(1-pyrazolyl)borato][(2*S*,3*R*)-*η*-(3,4,5)-6-(*E*)-ethylidene-2,5-dimethoxy-3,6-dihydro-2*H*-pyran-3-yl]molybdenum, (±)-113d.

Following the *general procedure,* **110b** (49 mg, 0.10 mmol, 1 equiv) was dissolved in THF (6 mL), and reacted with NaOMe (57 mg, 1.0 mmol, 10 equiv) for 4 h followed by adding solid Me_3OBF_4 (222 mg, 1.50 mmol, 15 equiv). Purification by column chromatography on silica gel (hexanes-EtOAc 3:1) afforded (±)-**113d** (35 mg, 66%) as a dark orange solid.

(±)-**113d**: TLC (R_f = 0.62, hexanes-EtOAc 2:1). IR (cm^{-1}): 2930 (m), 2482 (m), 2250 (w), 1926 (s), 1841 (s), 1502 (s), 1409 (s), 1305(s), 1239 (s). ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.34 (d, *J* = 1.6 Hz, 1H), 7.70 (d, *J* = 1.6 Hz, 1H), 7.66 (d, *J* = 2.4 Hz, 1H), 7.63 (d, *J* = 2.0 Hz, 1H), 7.58 (d, *J* = 2.0 Hz, 1H), 7.50 (d, *J* = 2.0 Hz, 1H), 6.22 (q, *J* = 2.4 Hz, 2H), 6.19 (t, *J* = 2.2 Hz, 1H), 5.35 (q, *J* = 7.8 Hz, 1H), 4.82 (d, *J* = 1.2 Hz, 1H), 4.08 (dd, *J* = 8.0, 1.6 Hz, 1H), 3.83 (d, *J* = 8.0 Hz, 1H), 3.46 (s, 3H), 3.01 (s, 3H), 2.07 (d, *J* = 8.0 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 232.0, 226.9, 146.8, 144.5, 140.5, 139.4, 137.0,

136.3, 135.7, 134.7, 109.6, 105.7, 105.5(2C), 99.5, 58.9, 56.3, 54.5, 52.6, 12.7. HRMS (ESI) Calcd for $C_{20}H_{24}BMoN_6O_5$ ($[M]^+$): 537.0950. Found: 537.0958.



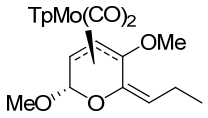
113e

(±)-Dicarbonyl[hydridotris(1-pyrazolyl)borato][(2*S*,3*R*)-η-(3,4,5)-6-(*Z*)-propylidene-2,5-dimethoxy-3,6-dihydro-2*H*-pyran-3-yl]molybdenum, (±)-113e.

Following the *general procedure,* **110c** (53 mg, 0.105 mmol, 1 equiv) was dissolved in THF (5 mL), and reacted with NaOMe (60 mg, 1.05 mmol, 10 equiv) for 4 h followed by adding solid Me_3OBF_4 (246 mg, 1.58 mmol, 15 equiv). Purification by column chromatography on silica gel (hexanes-EtOAc 3:1) afforded (±)-**113e** (41 mg, 71%) as a dark orange solid.

(±)-**113e**: TLC (R_f = 0.58, hexanes-EtOAc 2:1). IR (cm^{-1}): 2930 (w), 2482 (w), 1926 (s), 1841 (s), 1505 (w), 1409 (m), 1305(m), 1235 (m). ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.30 (d, *J* = 2.0 Hz, 1H), 7.70 (d, *J* = 2.0 Hz, 1H), 7.65 (d, *J* = 1.6 Hz, 1H), 7.62 (d, *J* = 2.4 Hz, 1H), 7.58 (d, *J* = 2.0 Hz, 1H), 7.50 (dd, *J* = 2.0, 0.6 Hz, 1H), 6.21 (t, *J* = 2.2 Hz, 1H), 6.20 (t, *J* = 2.4 Hz, 1H), 6.17 (t, *J* = 2.0 Hz, 1H), 5.56 (t, *J* = 7.2 Hz, 1H), 4.96 (d, *J* = 0.8 Hz, 1H), 4.09 (dd, *J* = 8.0, 1.6 Hz, 1H), 3.77 (d, *J* = 8.0 Hz, 1H), 3.48 (s, 3H), 3.01 (s, 3H), 2.37-2.18 (m, 2H), 1.04 (t, *J* = 7.4 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 232.2, 227.2, 146.7, 144.1, 141.0, 139.4, 136.3, 135.7, 134.7, 134.4, 113.0, 105.7, 105.5,

105.4, 99.8, 57.6, 56.2, 54.9, 52.4, 18.1, 14.7. HRMS (ESI) Calcd for $C_{21}H_{25}BMoN_6O_5$ ($[M+H]^+$): 551.1106. Found: 551.1110.



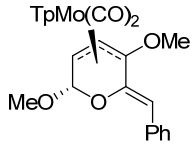
113f

(±)-Dicarbonyl[hydridotris(1-pyrazolyl)borato][(2*S*,3*R*)-η-(3,4,5)-6-(*E*)-propylidene-2,5-dimethoxy-3,6-dihydro-2*H*-pyran-3-yl]molybdenum, (±)-113f.

Following the *general procedure,* **110d** (48 mg, 0.096 mmol, 1 equiv) was dissolved in THF (5 mL), and reacted with NaOMe (54.3 mg, 0.96 mmol, 10 equiv) for 5 h followed by adding solid Me_3OBF_4 (141 mg, 0.96 mmol, 10 equiv). Purification by column chromatography on silica gel (hexanes-EtOAc 3:1) afforded (±)-**113f** (33 mg, 63%) as a dark orange solid. *The ^{13}C NMR spectra of **113f** displayed as a mixture of **113e** and **113f** since **113f** partially converted to **113e** in $CDCl_3$ during the ^{13}C NMR experiment.*

(±)-**113f**: TLC (R_f = 0.51, hexanes-EtOAc 3:1). IR (cm^{-1}): 2922 (m), 2482 (w), 1926 (s), 1841 (s), 1505 (s), 1409 (s), 1305 (s). ^1H NMR (400 MHz, $CDCl_3$): δ 8.34 (d, *J* = 2.0 Hz, 1H), 7.68 (d, *J* = 2.0 Hz, 1H), 7.66 (d, *J* = 2.4 Hz, 1H), 7.63 (d, *J* = 2.0 Hz, 1H), 7.59 (d, *J* = 2.0 Hz, 1H), 7.50 (d, *J* = 2.0 Hz, 1H), 6.22 (t, *J* = 2.4 Hz, 1H), 6.21 (t, *J* = 2.4 Hz, 1H), 6.19 (t, *J* = 2.2 Hz, 1H), 5.26 (t, *J* = 7.8 Hz, 1H), 4.82 (d, *J* = 1.1 Hz, 1H), 4.08 (dd, *J* = 8.4, 1.2 Hz, 1H), 3.84 (d, *J* = 8.4 Hz, 1H), 3.46 (s, 3H), 3.02 (s, 3H), 2.65-2.51 (m, 2H), 1.08 (t, *J* = 7.6 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 232.0, 226.8, 146.8, 144.4,

139.4(2C), 136.5, 136.3, 135.7, 134.7, 117.6, 105.7, 105.5(2C), 99.4, 58.8, 56.3, 54.5, 52.5, 20.3, 15.5. HRMS (ESI) Calcd for $C_{21}H_{26}BMoN_6O_5$ ($[M+H]^+$): 551.1106. Found: 551.1110.



113g

(±)-Dicarbonyl[hydridotris(1-pyrazolyl)borato][(2*S*,3*R*)-η-(3,4,5)-6-(*Z*)-benzylidene-2,5-dimethoxy-3,6-dihydro-2*H*-pyran-3-yl]molybdenum, (±)-113g.

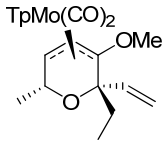
Following the *general procedure,* **110e** (110 mg, 0.20 mmol, 1 equiv) was dissolved in THF (8 mL), and reacted with NaOMe (114 mg, 2.0 mmol, 10 equiv) for 5 h followed by adding solid Me_3OBF_4 (296 mg, 2.0 mmol, 10 equiv). Purification by column chromatography on silica gel (hexanes-EtOAc 3:1) afforded (±)-**113g** (31 mg, 26%) as a brown solid.

(±)-**113g**: TLC (R_f = 0.40, hexanes-EtOAc 3:1). IR (cm^{-1}): 2930 (m), 2842 (m), 1926 (s), 1841 (s), 1505 (s), 1409 (s),1305 (s), 1235 (s). ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.31 (d, *J* = 1.6 Hz, 1H), 7.74 (d, *J* = 2.0 Hz, 1H), 7.71 (s, 1H), 7.69 (s, 1H), 7.67 (d, *J* = 1.6 Hz, 1H), 7.64 (d, *J* = 2.4 Hz, 1H), 7.61 (d, *J* = 2.0 Hz, 1H), 7.50 (d, *J* = 2.0 Hz, 1H), 7.29 (t, *J* = 7.6 Hz, 2H), 7.13 (d, *J* = 7.4 Hz, 1H), 6.44 (s, 1H), 6.24 (t, *J* = 2.2 Hz, 1H), 6.21 (t, *J* = 2.2 Hz, 1H), 6.20 (t, *J* = 2.4 Hz, 1H), 5.09 (s, 1H), 4.23 (dd, *J* = 8.4, 1.6 Hz, 1H), 3.94 (d, *J* = 8.0 Hz, 1H), 3.44 (s, 3H), 3.07 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 232.0, 226.9,

146.7, 144.2, 143.6, 139.4, 136.4, 135.8(2C), 134.7, 132.9, 129.1(2C), 128.2(2C), 126.1, 107.7, 105.8, 105.6, 105.5, 99.8, 59.0, 56.5, 55.0, 52.1. HRMS (ESI) Calcd for $C_{25}H_{25}BMoN_6O_5$ ($[M]^+$): 598.1028. Found: 598.1037.

General procedure for ionization/nucleophilic addition reaction of 113a and 113b.

In a Schlenk flask, molybdenum complexes **113a** or **113b** (1 equiv) was dissolved in CH_2Cl_2 at 0 ºC under argon. HBF_4 (54 wt% in Et_2O, 1.5 equiv.) was added dropwise to the reaction mixture and stirred for 5 min after which TLC indicated *almost* complete disappearance of starting material. Then the reaction was cooled to -78 ºC, commercially available Grignard or organolithium reagent (3 or 4 equiv) was added to the solution. After 10 min, the reaction was quenched with MeOH (1 mL) at -78 ºC, and then diluted with EtOAc and water. The organic layer was separated and washed with brine. The combined organic layers were dried over $MgSO_4$, and concentrated under low pressure. The residue was further purified by column chromatography on silica gel.



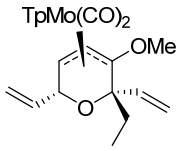
114a

(±)-Dicarbonyl[hydridotris(1-pyrazolyl)borato][(2*S*,3*S*,6*R*)-η-(3,4,5)-2-ethyl-3-methoxy-6-methyl-2-vinyl-3,6-dihydro-2*H*-pyran-3-yl]molybdenum, (±)-114a.

Following the *general procedure,* **113a** (70 mg, 0.124 mmol, 1 equiv) was dissolved in

CH_2Cl_2 (5 mL) at 0 ºC, and reacted with HBF_4 (26 μL, 0.186 mmol, 1.5 equiv) followed by addition of 3.0 M MeMgCl in THF (124 μL, 0.372 mmol, 3 equiv). Purification by column chromatography on silica gel (hexanes-EtOAc 3:1) afforded (±)-**114a** (56 mg, 83%) as a dark orange solid.

(±)-**114a**: TLC (R_f =0.69, hexanes-EtOAc 3:1). IR (cm^{-1}): 2988 (w), 2934 (m), 2482 (m), 1918 (s), 1818 (s), 1517 (m), 1432 (m), 1305(m), 1224 (m). ^{1}H NMR (600 MHz, $CDCl_3$): δ 8.27 (d, *J* = 1.8 Hz, 1H), 7.80 (d, *J* = 1.8 Hz, 1H), 7.66 (d, *J* = 2.4 Hz, 1H), 7.60 (d, *J* = 1.8 Hz, 1H), 7.50 (d, *J* = 1.8 Hz, 1H), 7.44 (d, *J* = 2.4 Hz, 1H), 6.22 (m, 4H), 5.20 (dd, *J* = 18.0, 0.9 Hz, 1H), 5.09 (d, *J* = 11.4 Hz, 1H), 4.21 (q, *J* = 6.6 Hz, 1H), 4.05 (d, *J* = 7.8 Hz, 1H), 3.76 (d, *J* = 7.8 Hz, 1H), 2.62 (s, 3H), 2.17-2.46 (m, 2H), 1.49 (d, *J* = 7.2 Hz, 3H), 0.98 (t, *J* = 7.5Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 233.2, 228.8, 146.9, 146.0, 145.5, 145.3, 139.3, 136.0, 135.3, 134.7, 112.8, 105.53, 105.52, 105.5, 77.2, 71.1, 61.8, 59.9, 52.7, 31.7, 27.2, 7.3. HRMS (ESI) Calcd for $C_{22}H_{27}BMoN_6O_4$ ($[M+H]^+$): 548.1235. Found: 548.1236.



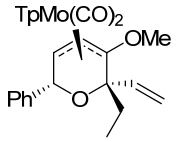
114b

(±)-Dicarbonyl[hydridotris(1-pyrazolyl)borato][(2*S*,3*S*,6*R*)-*η*-(3,4,5)-2-ethyl-2,6-divinyl-3-methoxy-3,6-dihydro-2*H*-pyran-3-yl]molybdenum, (±)-114b.

Following the *general procedure,* **113a** (30 mg, 0.053mmol, 1 equiv) was dissolved in

CH_2Cl_2 (1 mL) at 0 ºC, and reacted with HBF_4 (11 μL, 0.080 mmol, 1.5 equiv) followed by addition of 1.4 M VinylMgCl in THF (152 μL, 0.212 mmol, 4 equiv). Purification by column chromatography on silica gel (hexanes-EtOAc 3:1) afforded (±)-**114b** (27 mg, 90%) as a brown solid.

(±)-**114b**: TLC (R_f = 0.66, hexanes-EtOAc 3:1). IR (cm^{-1}): 2980 (w), 2937 (w), 2482 (w), 1918 (s), 1822 (s), 1505 (m), 1409 (m), 1305 (m), 1224 (m), 1119 (s). ^{1}H NMR (600 MHz, $CDCl_3$): δ 8.29 (d, *J* = 1.8 Hz, 1H), 7.79 (d, *J* = 1.8 Hz, 1H), 7.66 (d, *J* = 2.4 Hz, 1H), 7.60 (d, *J* = 2.4 Hz, 1H), 7.51 (d, *J* = 2.4 Hz, 1H), 7.44 (d, *J* = 1.8 Hz, 1H), 6.24 (dd, *J* = 17.1, 9.4 Hz, 1H), 6.20 (m, 3H), 6.16 (dd, *J* = 17.7, 11.1 Hz, 1H), 5.27 (d, *J* = 16.8 Hz, 1H), 5.17 (d, *J* = 18.0 Hz, 1H), 5.11 (d, *J* = 11.4 Hz, 1H), 5.08 (d, *J* = 10.2 Hz, 1H), 4.40 (d, *J* = 8.4 Hz, 1H), 4.07 (d, *J* = 8.4 Hz, 1H), 3.78 (d, *J* = 7.8 Hz, 1H), 2.62 (s, 3H), 2.18-2.48 (m, 2H), 0.96 (t, *J* = 7.2Hz, 3H). ^{13}C NMR (150 MHz, $CDCl_3$): δ 232.9, 228.6, 146.7, 146.0, 145.4, 144.9, 143.0, 139.3, 136.1, 135.4, 134.7, 115.9, 113.6, 105.59, 105.56, 105.52, 77.5, 76.6, 61.7, 57.2, 52.9, 31.3, 7.2. HRMS (ESI) Calcd for $C_{23}H_{27}BMoN_6O_4$ ($[M]^+$): 560.1235. Found: 548.1248.

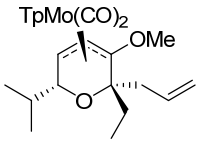


114c

(±)-Dicarbonyl[hydridotris(1-pyrazolyl)borato][(2*S*,3*S*,6*R*)-*η*-(3,4,5)-2-ethyl-3-methoxy-6-phenyl-2-vinyl-3,6-dihydro-2*H*-pyran-3-yl]molybdenum, (±)-114c.

Following the *general procedure,* **113a** (30 mg, 0.053mmol, 1 equiv) was dissolved in CH_2Cl_2 (1 mL) at 0 ºC, and reacted with HBF_4 (11 μL, 0.080 mmol, 1.5 equiv) followed by addition of 2.0 M PhMgCl in THF (80 μL, 0.159 mmol, 3 equiv). Purification by column chromatography on silica gel (hexanes-EtOAc 3:1) afforded (±)-**114c** (30 mg, 94%) as a dark orange solid.

(±)-**114c**: TLC (R_f = 0.53, hexanes-EtOAc 3:1). IR (cm^{-1}): 2980 (w), 2937 (w), 2482 (m), 1918 (s), 1826(s), 1515 (m), 1409 (m), 1305 (m), 1227 (m), 1119 (m). ^{1}H NMR (600 MHz, $CDCl_3$): δ 8.32 (d, *J* = 1.2 Hz, 1H), 7.82 (d, *J* = 1.2 Hz, 1H), 7.69 (d, *J* = 1.8 Hz, 1H), 7.66 (d, *J* = 7.2 Hz, 2H), 7.64 (d, *J* = 1.8 Hz, 1H), 7.55 (d, *J* = 1.8 Hz, 1H), 7.52 (d, *J* = 1.2 Hz, 1H), 7.33 (t, *J* = 7.5 Hz, 2H), 7.27 (d, *J* = 7.2 Hz, 1H), 6.23 (m, 3H), 5.40 (dd, *J* = 18.0, 10.8 Hz, 1H), 5.13 (s, 1H), 4.71 (d, *J* = 17.4 Hz, 1H), 4.55 (d, *J* = 10.8 Hz, 1H), 4.52 (d, *J* = 8.4 Hz, 1H), 4.03 (d, *J* = 7.8 Hz, 1H), 2.66 (s, 3H), 2.48-2.15 (m, 2H), 0.93 (t, *J* = 7.5 Hz, 3H). ^{13}C NMR (150 MHz, $CDCl_3$): δ 233.3, 229.1, 147.6, 146.1, 145.4, 144.1, 143.1, 139.2, 136.2, 135.5, 134.7, 129.5, 129.5, 127.6, 127.6, 127.3, 112.6, 105.6, 105.6, 105.6, 78.1, 74.7, 62.2, 55.1, 53.1, 31.1, 7.2. HRMS (ESI) Calcd for $C_{27}H_{29}BMoN_6O_4$ ($[M]^+$): 610.1392. Found: 560.1388.



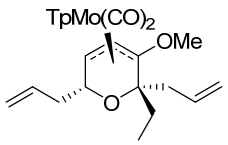
114d

(±)-Dicarbonyl[hydridotris(1-pyrazolyl)borato][(2*S*,3*S*,6*R*)-η-(3,4,5)-2-allyl-2-

ethyl-6-isopropyl-3-methoxy-3,6-dihydro-2*H*-pyran-3-yl]molybdenum, (±)-114d.

Following the *general procedure,* **113b** (32 mg, 0.055mmol, 1 equiv) was dissolved in CH_2Cl_2 (1 mL) at 0 ºC, and reacted with HBF_4 (11 μL, 0.080 mmol, 1.5 equiv) followed by addition of 2.0 M *i*PrMgCl in THF (83 μL, 0.166 mmol, 3 equiv). Purification by column chromatography on silica gel (hexanes-EtOAc 3:1) afforded **(**±)-**114d** (21 mg, 65%) as a dark orange solid.

(±)-**114d**: TLC (R_f = 0.56, hexanes-EtOAc 3:1). IR (cm^{-1}): 2941 (w), 2482 (w), 1918 (s), 1822 (s), 1513 (m), 1409 (m), 1305(m), 1220 (m), 1119 (m). ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.26 (d, *J* = 2.0 Hz, 1H), 7.74 (d, *J* = 1.6 Hz, 1H), 7.63 (d, *J* = 2.4 Hz, 1H), 7.59 (d, *J* = 2.4 Hz, 1H), 7.49 (d, *J* = 2.4 Hz, 1H), 7.42 (d, *J* = 2.0 Hz, 1H), 6.20-6.17 (m, 3H), 5.98-5.87 (m, 1H), 5.00 (d, *J* = 16.8 Hz, 1H), 4.94 (d, *J* = 10.0 Hz, 1H), 4.34 (d, *J* = 8.0 Hz, 1H), 3.65 (d, *J* = 8.0 Hz, 1H), 3.48 (d, *J* = 10.0 Hz, 1H), 2.90 (dd, *J* = 14.0, 6.4 Hz, 1H), 2.47 (dd, *J* = 13.6, 7.6 Hz, 1H), 2.46 (s, 3H), 2.36-2.18 (m, 2H), 1.93-1.83 (m, 1H), 1.11 (d, *J* = 6.4 Hz, 3H), 1.08 (d, *J* = 6.4 Hz, 3H), 1.10 (t, *J* = 7.4 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 234.0, 229.3, 148.4, 146.0, 145.6, 139.3, 136.0, 135.6, 135.3, 134.6, 115.4, 105.5, 105.47, 105.43, 81.1, 78.4, 62.4, 55.8, 55.2, 48.2, 36.9, 27.6, 20.6, 20.5, 7.1. HRMS (ESI) Calcd for $C_{25}H_{33}BMoN_6O_4$ ($[M]^+$): 590.1705. Found: 590.1704.



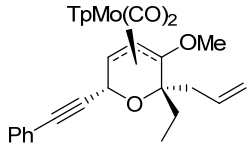
114e

(±)-Dicarbonyl[hydridotris(1-pyrazolyl)borato][(2*S*,3*S*,6*R*)-η-(3,4,5)-2.6-diallyl-2-ethyl-3-methoxy-3,6-dihydro-2*H*-pyran-3-yl]molybdenum, (±)-114e.

Following the *general procedure,* **113b** (215 mg, 0.37mmol, 1 equiv) was dissolved in CH_2Cl_2 (5 mL) at 0 ºC, and reacted with HBF_4 (77.3 μL, 0.56 mmol, 1.5 equiv) followed by addition of 2.0 M AllylMgCl in THF (560 μL, 1.12 mmol, 3 equiv). Purification by column chromatography on silica gel (hexanes-EtOAc 3:1) afforded (±)-**114e** (180 mg, 82%) as a dark orange solid.

(±)-**114e**: TLC (R_f = 0.65, hexanes-EtOAc 3:1). IR (cm^{-1}): 2961 (w), 2482 (w), 1918 (s), 1822 (s), 1513 (m), 1409 (m), 1305 (m), 1220 (m), 1119 (m). ^{1}H NMR (600 MHz, $CDCl_3$): δ 8.26 (d, *J* = 2.4 Hz, 1H), 7.75 (d, *J* = 1.8 Hz, 1H), 7.65 (d, *J* = 2.4 Hz, 1H), 7.59 (d, *J* = 1.8 Hz, 1H), 7.50 (d, *J* = 2.4 Hz, 1H), 7.41 (d, *J* = 2.4 Hz, 1H), 6.20-6.19 (m, 3H), 5.99-5.89 (m, 2H), 5.21 (dd, *J* = 17.1, 1.5 Hz, 1H), 5.15 (d, *J* = 10.2 Hz, 1H), 5.04 (dd, *J* = 17.1, 1.5 Hz, 1H), 4.99 (d, *J* = 10.2 Hz, 1H), 4.18 (d, *J* = 8.4 Hz, 1H), 4.07 (dd, *J* = 8.4, 5.4 Hz, 1H), 3.64 (d, *J* = 8.4 Hz, 1H), 2.78-2.71 (m, 2H), 2.61 (dd, *J* = 14.4, 8.2 Hz, 1H), 2.53 (s, 3H), 2.47 (m, 1H), 2.32-2.23 (m, 2H), 1.01 (d, *J* = 7.5 Hz, 3H), 1.08 (d, *J* = 6.4 Hz, 3H), 1.10 (t, *J* = 7.4 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 233.4, 228.8, 149.3, 146.0, 145.4, 138.3, 136.0, 135.8, 135.3(2C), 134.7, 117.0, 115.9, 105.51, 105.47(2C), 77.9, 74.3, 61.0, 57.1, 52.5, 48.8, 46.1, 28.4, 7.5. HRMS (ESI) Calcd for

$C_{25}H_{32}BMoN_6O_4$ ($[M+H]^+$): 589.1627. Found: 589.1624.



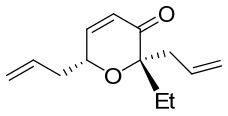
114f

(±)-Dicarbonyl[hydridotris(1-pyrazolyl)borato][(2*S*,3*S*,6*R*)-η-(3,4,5)-2-allyl-2-ethyl-3-methoxy-6-(phenylethynyl)-3,6-dihydro-2*H*-pyran-3-yl]molybdenum, (±)-114f.

Following the *general procedure,* **113b** (65 mg, 0.11mmol, 1 equiv) was dissolved in CH_2Cl_2 (3 mL) at 0 ºC, and reacted with HBF_4 (24 μL, 0.17 mmol, 1.5 equiv) followed by addition of 1.0 M Lithium phenylacetylide in THF (450 μL, 0.45 mmol, 4 equiv). Purification by column chromatography on silica gel (hexanes-EtOAc 3:1) afforded (±)-**114f** (54 mg, 74%) as a dark orange solid.

(±)-**114f**: TLC (R_f = 0.53, hexanes-EtOAc 3:1). IR (cm^{-1}): 2482 (w), 1922 (s), 1826 (s), 1505 (m), 1409 (m), 1305(m), 1220 (m), 1119 (m). ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.28 (d, *J* = 1.6 Hz, 1H), 7.76 (d, *J* = 2.0 Hz, 1H), 7.66 (d, *J* = 1.6 Hz, 1H), 7.61 (d, *J* = 2.0 Hz, 1H), 7.51 (m, 2H), 7.45 (m, 2H), 7.32 (m, 3H), 6.21 (m, 3H), 6.13 (m, 1H), 5.10 (d, *J* = 16.0 Hz, 1H), 5.02 (d, *J* = 10.0 Hz, 1H), 4.92 (d, *J* = 0.8 Hz, 1H), 4.31 (d, *J* = 7.8, 1.0 Hz, 1H), 3.73 (d, *J* = 8.0 Hz, 1H), 3.18 (dd, *J* = 14.4, 5.2 Hz, 1H), 3.05 (dd, *J* = 14.6, 8.6 Hz, 1H), 2.62 (s, 3H), 2.27 (m, 2H), 1.06 (t, *J* = 7.4 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 233.0, 228.4, 150.2, 146.2, 145.5, 139.7, 136.4, 135.8, 135.7, 135.0, 131.6 (2C), 128.5

(2C), 128.4, 123.3, 116.1, 105.9, 105.8, 105.8, 93.0, 85.2, 78.8, 62.9, 59.8, 57.4, 53.2, 46.3, 28.8, 8.1. HRMS (ESI) Calcd for $C_{30}H_{32}BMoN_6O_4$ ($[M+H]^+$): 649.1628. Found: 649.1618.



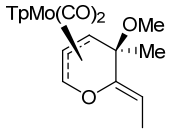
116

(±)-(2*S*,6*R*)-2,6-diallyl-2-ethyl-2*H*-pyran-3(6H)-one, (±)-116.

To a solution of molybdenum complex (±)-**114e** (121 mg, 0.21 mmol, 1.0 equiv) in THF/H_2O (3:1, 12 mL) was added Et_3N (43 μL, 0.62 mmol, 1.5 equiv) at 0 ^oC. Then a solution of ceric ammonium nitrate (905 mg, 1.65 mmol, 8.0 equiv) in water (3 mL) was added dropwise over 5 min. Upon addition, the orange solution changed to light yellow. The reaction was allowed to stir at room temperature for 10 minutes, and then partitioned between CH_2Cl_2 (20 mL) and water (20 mL). The organic layers were collected and washed with brine, dried over $MgSO_4$, concentrated and purified by column chromatography on silica gel (hexanes-EtOAc 6:1) to afford (±)-**116** as a colorless oil (24 mg, 56%).

(±)-**116**: TLC (R_f = 0.60, hexanes-EtOAc 6:1). IR (cm^{-1}): 2980 (m), 2829 (m), 1687 (s), 1069 (m). ^1H NMR (400 MHz, $CDCl_3$): δ 6.43 (dd, *J* = 10.2, 1.4 Hz, 1H), 5.60 (dd, *J* = 10.4, 2.4 Hz, 1H), 5.85 (m, 2H), 5.17-5.02 (m, 4H), 4.45 (m, 1H), 2.58-2.36 (m, 4H), 1.86-1.74 (m, 1H), 1.66-1.37 (m, 1H), 0.91 (t, *J* = 7.4 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 198.7, 149.6, 133.4, 133.3, 125.5, 118.1, 117.8, 82.9, 68.0, 39.3, 38.4, 25.6,

7.5. HRMS (ESI) Calcd for $C_{13}H_{19}O_2$ ($[M+H]^+$): 207.1380. Found: 207.1377.



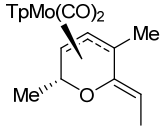
132

(±)-Dicarbonyl[hydridotris(1-pyrazolyl)borato][(2*S*,5*S*)-η-(2,3,4)-6-(*Z*)-ethylidene-5-methoxy-5-methyl-5,6-dihydro-2*H*-pyran-2-yl]molybdenum, (±)-132.

In a Schlenk flask, molybdenum complexes **113c** (41 mg, 0.077 mmol, 1.0 equiv) was dissolved in CH_2Cl_2 (2 mL) at 0 ºC under argon. HBF_4 (54 wt% in Et_2O, 16 μL, 0.12 mmol, 1.5 equiv) was added dropwise to the reaction mixture and stirred for 5 min after which TLC indicated *almost* complete disappearance of starting material. Then the reaction was cooled to -78 ºC, MeMgCl (3.0 M in THF, 115 μL, 0.35 mmol, 4.5 equiv) was added dropwise to the solution. After 10 min, the reaction was quenched with MeOH (1 mL) at -78 ºC, and then diluted with EtOAc and water. The organic layer was separated and washed with brine. The combined organic layers were dried over $MgSO_4$, and concentrated under low pressure. The residue was further purified by column chromatography on silica gel (hexanes-EtOAc 3:1) to afford (±)-**132** (38 mg, 95%) as a yellow solid.

(±)-**132**: TLC (R_f = 0.71, hexanes-EtOAc 2:1). IR (cm^{-1}): 2482 (m), 1953 (s), 1868 (s), 1505 (m), 1407 (s), 1305 (s), 1220 (s). ^1H NMR (400 MHz, $CDCl_3$): δ 8.51 (d, *J* = 1.8 Hz, 1H), 7.84 (d, *J* = 1.8 Hz, 1H), 7.74 (d, *J* = 2.0 Hz, 1H), 7.56 (s, 2H), 7.47 (d, *J* = 2.1

Hz, 1H), 7.05 (dd, *J* = 4.2, 2.2 Hz, 1H), 6.25 (t, *J* = 2.2 Hz, 1H), 6.19 (t, *J* = 2.2 Hz, 1H), 6.18 (t, *J* = 2.2 Hz, 1H), 4.93 (q, *J* = 7.2 Hz, 1H), 4.67 (dd, *J* = 7.6, 2.2 Hz, 1H), 3.59 (s, 3H), 3.40 (dd, *J* = 7.8, 4.4 Hz, 1H), 1.64 (s, 3H), 1.52 (d, *J* = 7.2 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 227.2, 225.5, 151.1, 146.9, 142.0, 141.8, 136.1, 136.0, 134.4, 108.6, 106.0, 105.6, 105.4, 101.1, 76.3, 68.9, 57.1, 49.1, 31.4, 9.6. HRMS (ESI) Calcd for $C_{20}H_{24}BMoN_6O_4$ ($[M+H]^+$): 521.1001. Found: 521.1023.



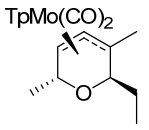
130

(±)-Dicarbonyl[hydridotris(1-pyrazolyl)borato][(3*S*,6*R*)-*η*-(3,4,5)-3,6-dimethyl-2-(*Z*)-ethylidene-2,6-dihydro-6*H*-pyran-3-yl]molybdenum, (±)-130.

In a Schlenk flask, molybdenum complexes **132** (45 mg, 0.087 mmol, 1.0 equiv) was dissolved in CH_2Cl_2 (2 mL) at -40 ºC under argon. HBF_4 (54 wt% in Et_2O, 18 μL, 0.13 mmol, 1.5 equiv) was added dropwise to the reaction mixture and stirred for 5 min after which TLC indicated disappearance of starting material. Then the reaction was cooled to -78 ºC, MeMgCl (3.0 M in THF, 130 μL, 0.39 mmol, 4.5 equiv) was added dropwise to the solution. After 10 min, the reaction was quenched with MeOH (1 mL) at -78 ºC, and then diluted with EtOAc (10 mL) and water. The organic layer was separated and washed with brine (5 mL). The combined organic layers were dried over $MgSO_4$, and concentrated under low pressure. The residue was further purified by careful column chromatography on silica gel (hexanes-CH_2Cl_2 1:1) to afford (±)-**130** (21 mg, 50%) as a

yellow solid.

(±)-**130**: TLC (R_f = 0.38, hexanes-CH_2Cl_2 1:1). IR (cm^{-1}): 2484 (w), 1924 (s), 1841 (s), 1405 (m), 1306 (m), 1216 (m). ^1H NMR (400 MHz, $CDCl_3$): δ 8.46 (d, *J* = 2.1 Hz, 1H), 7.68 (d, *J* = 1.8 Hz, 1H), 7.63 (s, 2H), 7.60 (d, *J* = 1.8 Hz, 1H), 7.46 (d, *J* = 2.4 Hz, 1H), 6.23 (t, *J* = 2.0 Hz, 1H), 6.21 (t, *J* = 2.0 Hz, 1H), 6.17 (t, *J* = 2.0 Hz, 1H), 5.01 (q, *J* = 6.7 Hz, 1H), 4.34 (q, *J* = 6.4 Hz, 1H), 4.01 (dd, *J* = 7.4, 1.6 Hz, 1H), 3.95 (d, *J* = 7.4 Hz, 1H), 1.85 (s, 3H), 1.70 (d, *J* = 7.2 Hz, 3H), 1.47 (d, *J* = 6.4 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 232.8, 226.6, 148.5, 146.9, 145.5, 139.2, 136.5, 135.9, 134.44, 105.7, 105.5, 105.2, 102.7, 96.3, 74.5, 69.8, 60.2, 25.2, 22.3, 10.4. HRMS (ESI) Calcd for $C_{20}H_{24}BMoN_6O_3$ ($[M+H]^+$): 505.1052. Found: 505.1052.



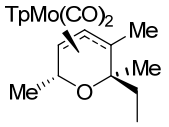
134

(±)-Dicarbonyl[hydridotris(1-pyrazolyl)borato][(2*R*,3*S*,6*R*)-*η*-(3,4,5)-3,6-dimethyl-2-ethyl-3,6-dihydro-2*H*-pyran-3-yl]molybdenum, (±)-134.

In a Schlenk flask, molybdenum complexes **130** (20 mg, 0.040 mmol, 1.0 equiv) was dissolved in CH_2Cl_2 (3 mL) at 0 ºC under argon. HBF_4 (54 wt% in Et_2O, 16 μL, 0.12 mmol, 3 equiv) was added dropwise to the reaction mixture and stirred for 15 min after which TLC indicated disappearance of starting material. Then $NaCNBH_3$ (1.0 M in THF, 160 μL, 0.16 mmol, 4 equiv) was added dropwise to the solution. After 10 min at 0 ºC, the reaction was warmed to room temperature, and stirred for additional 30 min. Then the

reaction mixture was directly put on a silica gel column for purification (hexanes-EtOAc 2:1) to afford (±)-**134** (18 mg, 90%) as a yellow solid.

(±)-**134**: TLC (R_f = 0.61, hexanes-EtOAc 2:1). IR (cm^{-1}): 2472 (w), 1930 (s), 1841 (s), 1405 (m), 1305 (m), 1212 (m), 1050 (m). ^1H NMR (400 MHz, $CDCl_3$): δ 8.46 (d, *J* = 2.0 Hz, 1H), 7.80 (d, *J* = 2.0 Hz, 1H), 7.62 (d, *J* = 2.0 Hz, 1H), 7.60 (d, *J* = 2.0 Hz, 1H), 7.52 (d, *J* = 2.0 Hz, 1H), 7.46 (d, *J* = 1.6 Hz, 1H), 6.19 (m, 3H), 4.13 (t, *J* = 5.6 Hz, 1H), 3.98-3.90 (m, 2H), 3.72 (dd, *J* = 9.2, 3.6 Hz, 1H), 1.95 (m, 2H), 1.75 (s, 3H), 1.47 (d, *J* = 6.4 Hz, 3H), 0.95 (t, *J* = 7.6 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 233.3, 228.6, 146.3, 146.1, 139.5, 136.4, 135.6, 134.2, 105.5, 105.4, 105.1, 99.3, 77.9, 72.8, 68.3, 64.6, 24.4, 23.7, 21.5, 11.5. HRMS (ESI) Calcd for $C_{20}H_{25}BMoN_6O_3$ ($[M]^+$): 506.1130. Found: 506.1145.



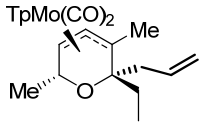
135

(±)-Dicarbonyl[hydridotris(1-pyrazolyl)borato][(2*R*,3*S*,6*R*)-*η*-(3,4,5)-2-ethyl-2,3,6-trimethyl-3,6-dihydro-2*H*-pyran-3-yl]molybdenum, (±)-135.

In a Schlenk flask, molybdenum complexes **130** (6 mg, 0.012 mmol, 1.0 equiv) was dissolved CH_2Cl_2 (1 mL) at 0 ºC under argon. HBF_4 (54 wt% in Et_2O, 2.5 μL, 0.018 mmol, 1.5 equiv) was added to the reaction mixture and stirred for 5 min. Then the reaction was cooled to -78 ºC, MeMgCl (3.0 M in THF, 16 μL, 0.048 mmol, 4 equiv) was added dropwise to the solution. After 10 min at -78 ºC, the cold reaction mixture was

directly put on a silica gel column for purification (hexanes-CH_2Cl_2 1:2) to afford (±)-**135** (4 mg, 67%) as a yellow solid.

(±)-**135**: TLC (R_f = 0.47, hexanes-CH_2Cl_2 1:2). ^{1}H NMR (600 MHz, $CDCl_3$): δ 8.38 (d, *J* = 1.8 Hz, 1H), 7.80 (d, *J* = 2.4 Hz, 1H), 7.63 (d, *J* = 1.8 Hz, 1H), 7.59 (d, *J* = 1.8 Hz, 1H), 7.52 (d, *J* = 1.2 Hz, 1H), 7.45 (d, *J* = 1.8 Hz, 1H), 6.19 (m, 3H), 4.23 (q, *J* = 7.2 Hz, 1H), 4.19 (d, *J* = 7.2 Hz, 1H), 4.13 (d, *J* = 6.6 Hz, 1H), 2.25 (m, 1H), 1.81 (m, 1H), 1.67 (s, 3H), 1.54 (s, 3H), 1.52 (d, *J* = 6.6 Hz, 3H), 0.94 (t, *J* = 7.6 Hz, 3H).



136

(±)-Dicarbonyl[hydridotris(1-pyrazolyl)borato][(2*S*,3*S*,6*R*)-*η*-(3,4,5)-2-allyl-3,6-dimethyl-2-ethyl-3,6-dihydro-2*H*-pyran-3-yl]molybdenum, (±)-136.

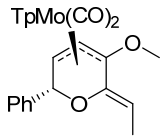
In a Schlenk flask, molybdenum complexes **130** (20 mg, 0.040 mmol, 1.0 equiv) was dissolved in CH_2Cl_2 (3 mL) at 0 ºC under argon. HBF_4 (54 wt% in Et_2O, 11 μL, 0.08 mmol, 2 equiv) was added dropwise to the reaction mixture and stirred for 10 min after which TLC indicated disappearance of starting material. Then the reaction was cooled to -78 ºC, allyl magnesium chloride (2.0 M in THF, 80 μL, 0.16 mmol, 4 equiv) was added dropwise to the solution. The color of the reaction changed from dark orange to yellow. After 10 min at 0 ºC, the reaction was quenched with H_2O (1 mL), diluted with CH_2Cl_2 and H_2O. The organic layer was separated and washed with brine. The combined organic layers were dried over $MgSO_4$, and concentrated under low pressure. The residue was

further purified by column chromatography on silica gel (hexanes-CH_2Cl_2 1:1) to afford (±)-**136** (14 mg, 65%) as a yellow solid. ***136*** *was slowly converted to* ***137*** *on rotary evaporato upon heating.*

(±)-**136**: TLC (R_f = 0.47, hexanes-CH_2Cl_2 1:1). ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.37 (d, *J* = 2.0 Hz, 1H), 7.80 (d, *J* = 2.0 Hz, 1H), 7.63 (d, *J* = 1.6 Hz, 1H), 7.59 (d, *J* = 1.6 Hz, 1H), 7.51 (d, *J* = 2.0 Hz, 1H), 7.45 (dd, *J* = 2.4, 0.8 Hz, 1H), 6.20 (m, 3H), 6.09 (m, 1H), 5.12-5.01 (m, 2H), 4.26 (q, *J* = 7.2 Hz, 1H), 4.20 (d, *J* = 7.6 Hz, 1H), 4.16 (d, *J* = 7.6 Hz, 1H), 2.79-2.58 (m, 2H), 2.24-2.10 (m, 2H), 1.67 (s, 3H), 1.56 (s, 3H), 1.01 (t, *J* = 7.6 Hz, 3H).

General procedure for synthesis alkylidene 138 *via* inonizaion/nucleophilic addition reaction

In a Schlenk flask, molybdenum complex **113** (1 equiv) was dissolved in CH_2Cl_2 at 0 ºC to -20 ºC under argon. HBF_4 (54 wt% in Et_2O, 1.5 equiv.) was added dropwise to the reaction mixture and stirred for 5 to 10 min. Then the reaction was cooled to -78 ºC, commercially available Grignard (4 to 4.5 equiv) was added to the solution. After 10 min, the reaction was quenched with MeOH (1 mL) at -78 ºC, and diluted with EtOAc and water. The organic layers were separated and washed with brine. The combined organic layers were dried over $MgSO_4$, and concentrated under low pressure. The residue was further purified by column chromatography on silica gel.

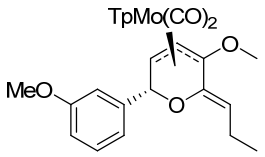


138a

(±)-Dicarbonyl[hydridotris(1-pyrazolyl)borato][(3*S*,6*R*)-η-(3,4,5)-2-(*Z*)-ethylidene-3-methoxy-3,6-dihydro-2*H*-pyran-3-yl]molybdenum, (±)-138a.

Following the *general procedure,* **113c** (230 mg, 0.43 mmol, 1 equiv) was dissolved in CH_2Cl_2 (4 mL) at 0 ºC, and reacted with HBF_4 (0.12 mL, 0.86 mmol, 2 equiv) followed by addition of 2.0 M PhMgCl in THF (0.97 mL, 1.93 mmol, 4.5 equiv). Purification by column chromatography on silica gel (hexanes-EtOAc 3:1) afforded **(**±)-**138a** (140 mg, 74%) as an orange solid.

(±)-**138a**: TLC (R_f = 0.40, hexanes-EtOAc 3:1). IR (cm^{-1}): 2481 (w), 1921 (s), 1837 (s), 1406 (m), 1305 (m), 1234 (m). ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.35 (d, *J* = 1.6 Hz, 1H), 7.74 (d, *J* = 2.0 Hz, 1H), 7.66 (d, *J* = 1.6 Hz, 1H), 7.62 (d, *J* = 2.0 Hz, 1H), 7.51 (t, *J* = 2.0 Hz, 2H), 7.45 (d, *J* = 7.4 Hz, 2H), 7.39 (t, *J* = 7.0 Hz, 2H), 7.31 (d, *J* = 7.4 Hz, 1H), 6.22 (t, *J* = 2.0 Hz, 1H), 6.19 (t, *J* = 2.0 Hz, 1H), 6.18 (t, *J* = 2.3 Hz, 1H), 5.50 (q, *J* = 7.4 Hz, 1H), 5.23 (s, 1H), 4.25 (dd, *J* = 8.2, 1.6 Hz, 1H), 3.70 (d, *J* = 8.2 Hz, 1H), 2.93 (s, 3H), 1.80 (d, *J* = 7.0 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 232.0, 227.5, 146.9, 145.7, 144.6, 144.4, 139.5, 136.5, 135.8, 134.9, 131.8, 128.7 (2C), 127.5, 125.7 (2C), 105.8, 105.6 (2C), 102.2, 75.9, 57.5, 56.9, 54.9, 10.3. HRMS(ESI) Calcd for $C_{25}H_{26}BMoN_6O_4$ ($[M+H]^+$): 583.1157. Found: 583.1162.



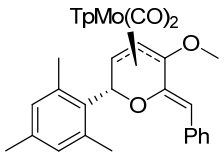
138b

(±)-Dicarbonyl[hydridotris(1-pyrazolyl)borato][(3*S*,6*R*)-η-(3,4,5)-3-methoxy-6-(3-methoxlphenyl)-2-(*Z*)-propylidene-3,6-dihydro-2*H*-pyran-3-yl]molybdenum, (±)-138b.

Following the *general procedure,* **113e** (13 mg, 0.024 mmol, 1 equiv) was dissolved in CH_2Cl_2 (1 mL) at 0 ºC, and reacted with HBF_4 (4.9 μL, 0.036 mmol, 1.5 equiv) followed by addition of 3-methoxyphenylmagnesium bromide (1.0 M in THF, 95 μL, 0.96 mmol, 4 equiv). Purification by column chromatography on silica gel (hexanes-EtOAc 4:1) afforded (±)-**138b** (12 mg, 81%) as an orange solid.

(±)-**138b**: TLC (R_f = 0.43, hexanes-EtOAc 3:1). IR (cm^{-1}): 2964 (ws), 2934(w), 2482 (w), 1926 (s), 1841 (s), 1602 (m), 1505 (m), 1409 (m), 1305 (m). ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.35 (d, *J* = 2.0 Hz, 1H), 7.74 (d, *J* = 2.0 Hz, 1H), 7.66 (d, *J* = 2.4 Hz, 1H), 7.62 (d, *J* = 2.4 Hz, 1H), 7.51 (d, *J* = 1.2 Hz, 2H), 7.30 (t, *J* = 3.8 Hz, 1H), 7.05 (d, *J* = 7.2 Hz, 1H), 7.06 (t, *J* = 2.4 Hz, 1H), 6.84 (dd, *J* = 8.0, 2.0 Hz, 1H), 6.23 (t, *J* = 2.0 Hz, 1H), 6.18 (m, 2H), 5.45 (t, *J* = 7.4 Hz, 1H), 5.17 (s, 1H), 4.23 (dd, *J* = 8.4, 1.6 Hz, 1H), 3.83 (s, 3H), 3.71 (d, *J* = 8.0 Hz, 1H), 2.94 (s, 3H), 2.29 (m, 2H), 1.00 (d, *J* = 7.4 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 231.8, 226.9, 159.6, 147.2, 146.7, 144.3, 143.2, 139.3, 136.3, 135.7, 134.7, 131.2, 129.4, 118.0, 112.5, 111.4, 110.0, 105.6, 105.4(2C), 75.5, 57.1, 57.0, 55.2, 54.8, 18.1, 14.8. HRMS(ESI) Calcd for $C_{27}H_{30}BMoN_6O_5$

([M+H]$^+$): 627.1419. Found: 627.1427.



138c

(±)-Dicarbonyl[hydridotris(1-pyrazolyl)borato][(3*S*,6*R*)-η-(3,4,5)-2-(*Z*)-benzyliden-3-methoxy-6-mesityl-3,6-dihydro-2*H*-pyran-3-yl]molybdenum, (±)-138c.

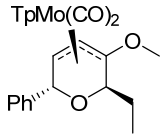
Following the *general procedure,* **113g** (28 mg, 0.047 mmol, 1 equiv) was dissolved in CH_2Cl_2 (1 mL) at -20 ºC, and reacted with HBF_4 (10 μL, 0.07 mmol, 1.5 equiv) followed by addition of 2-mesityl magnesium bromide (1.0 M in THF, 188 μL, 0.19 mmol, 4 equiv). Purification by column chromatography on silica gel (hexanes-EtOAc 4:1) afforded (±)-**138c** (20 mg, 62%) as an orange solid.

(±)-**138c**: TLC (R_f = 0.46 hexanes-EtOAc 3:1). ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.33 (d, *J* = 2.4 Hz, 1H), 7.87 (d, *J* = 2.0 Hz, 1H), 7.68 (d, *J* = 2.4 Hz, 1H), 7.63 (s, 1H), 7.62(s, 1H), 7.60 (s, 1H), 7.51 (d, *J* = 2.4 Hz, 1H), 7.45 (d, *J* = 2.0 Hz, 1H), 7.20 (t, *J* = 7.8 Hz, 2H), 7.02 (t, *J* = 7.2 Hz, 1H), 6.90(s, 2H), 6.25 (t, *J* = 2.2 Hz, 1H), 6.22 (t, *J* = 2.2 Hz, 1H), 6.18 (t, *J* = 2.0 Hz, 1H), 6.17 (s, 1H), 5.93 (s, 1H), 4.27 (d, *J* = 8,8 Hz, 1H), 3.97 (d, *J* = 8,8 Hz, 1H), 2.92 (s, 3H), 2.48 (s, 6H), 2.30 (s, 3H).

General procedure for the protonation/hydride addition reaction of alkylidenes 138

In a Schlenk flask, molybdenum complexes **138** (1 equiv) was dissolved in CH_2Cl_2 at 0

ºC under argon. A solution of HBF_4 (54 wt% in Et_2O, 1.5 equiv.) was added to the reaction and stirred for 10 min. Then $NaCNBH_3$ (1.0 M in THF, 4 equiv) was added dropwise to the reaction mixture. After 10 min at 0 ºC, the reaction was slowly warmed to room temperature for 30 min. Then the reaction mixture was directly put on a silica gel column for purification. (Or, on large scale, the reaction mixture was partitioned between water and CH_2Cl_2. The aqueous layer was separated and extracted with CH_2Cl_2. The combined organic layers were dried over $MgSO_4$, filtered and concentrated under low pressure. The residue was further purified by column chromatography on silica gel.



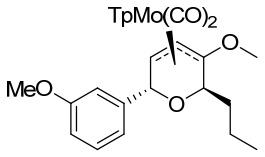
142a

(±)-Dicarbonyl[hydridotris(1-pyrazolyl)borato][(2*R*,3*S*,6*R*)-η-(3,4,5)-2-ethyl-3-methoxy-6-phenyl-3,6-dihydro-2*H*-pyran-3-yl]molybdenum, (±)-142a.

Following the *general procedure,* **138a** (24 mg, 0.041 mmol, 1 equiv) was dissolved in CH_2Cl_2 (1 mL) at 0 ºC, and reacted with HBF_4 (8.6 μL, 0.062 mmol, 1.5 equiv) followed by addition of 1.0 M $NaCNBH_3$ in THF (165 μL, 0.164 mmol, 4 equiv). Purification by column chromatography on silica gel (hexanes-EtOAc 3:1) afforded (±)-**142a** (22 mg, 92%) as an orange solid.

(±)-**142a**: TLC (R_f = 0.45, hexanes-EtOAc 3:1). IR (cm^{-1}): 2482 (m), 2250 (w), 1922 (s), 1830 (s), 1505 (m), 1432 (m), 1305 (m), 1220 (m), 1117 (m), 1047 (s). ^1H NMR (400

MHz, $CDCl_3$): δ 8.37 (d, *J* = 1.8 Hz, 1H), 7.81 (d, *J* = 2.0 Hz, 1H), 7.70 (d, *J* = 7.4 Hz, 2H), 7.67 (d, *J* = 2.0 Hz, 1H), 7.63 (d, *J* = 2.2 Hz, 1H), 7.56 (d, *J* = 1.6 Hz, 1H), 7.52 (d, *J* = 2.0 Hz, 1H), 7.41 (t, *J* = 7.4 Hz, 2H), 7.34 (d, *J* = 7.0 Hz, 1H), 6.23 (t, *J* = 1.6 Hz, 1H), 6.23 (t, *J* = 2.0 Hz, 1H), 6.20 (t, *J* = 2.2 Hz, 1H), 5.03 (s, 1H), 4.30 (dd, *J* = 7.8, 1.4 Hz, 1H), 3.90 (d, *J* = 8.0 Hz, 1H), 3.66 (dd, *J* = 8.2, 4.2 Hz, 1H), 2.79 (s, 3H), 2.20-2.07 (m, 2H), 0.91 (t, *J* = 7.4 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 232.0, 229.4, 146.1, 145.2, 142.1, 141.5, 139.2, 136.2, 135.6, 134.6, 128.3 (2C), 128.2 (2C), 127.7, 105.6, 105.5 (2C), 74.0, 71.4, 59.7, 55.2, 54.2, 22.1, 10.8. HRMS (ESI) Calcd for $C_{25}H_{28}BMoN_6O_4$ ($[M+H]^+$): 585.1314. Found: 585.1320.



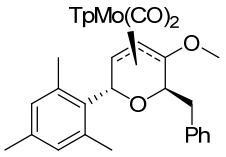
142b

(±)-Dicarbonyl[hydridotris(1-pyrazolyl)borato][(2*R*,3*S*,6*R*)-*η*-(3,4,5)-3-methoxy-6-(3-mthoxylphenyl)-2-propyl-3,6-dihydro-2*H*-pyran-3-yl]molybdenum, (±)-142b.

Following the *general procedure,* **138b** (12 mg, 0.019 mmol, 1 equiv) was dissolved in CH_2Cl_2 (1 mL) at 0 ºC, and reacted with HBF_4 (8.6 μL, 0.062 mmol, 1.5 equiv) followed by addition of $NaCNBH_3$ (1.0 M in THF, 79.6 μL, 0.077 mmol, 4 equiv). Purification by column chromatography on silica gel (hexanes-EtOAc 3:1) afforded (±)-**142b** (10 mg, 83%) as an orange solid.

(±)-**142a**: TLC (R_f = 0.38, hexanes-EtOAc 3:1). IR (cm^{-1}): 2961 (w), 2937 (w), 2482

(w), 1918 (s), 1826 (s), 1598 (m), 1505 (m), 1409 (m), 1305 (m). ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.36 (d, *J* = 2.0 Hz, 1H), 7.82 (d, *J* = 2.4 Hz, 1H), 7.66 (d, *J* = 2.4 Hz, 1H), 7.63 (d, *J* = 2.4 Hz, 1H), 7.55 (d, *J* = 1.6 Hz, 1H), 7.52 (t, *J* = 2.4 Hz, 1H), 7.35-7.29 (m, 2H), 7.25 (m, 1H), 6.88 (dt, *J* = 7.2, 2.0 Hz, 1H), 6.23 (m, 2H), 6.20 (t, *J* = 2.2 Hz, 1H), 4.99 (s, 1H), 4.27 (dd, *J* = 8.2, 1.4 Hz, 1H), 3.87 (d, *J* = 8.4 Hz, 1H), 3.84 (s, 3H), 3.76 (dd, *J* = 8.8, 3.2 Hz, 1H), 2.79 (s, 3H), 2.17-1.99 (m, 2H), 1.60-1.48 (m, 1H), 1.29-1.16 (m, 1H), 0.85 (t, *J* = 8.2 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 232.0, 229.3, 159.4, 146.1, 145.2, 143.2, 142.1, 139.2, 136.2, 135.6, 134.6, 129.1, 120.6, 114.2, 112.9, 105.6, 105.5 (2C), 73.9, 69.7, 59.6, 55.2, 55.0, 54.3, 30.7, 19.5, 13.9. HRMS(ESI) Calcd for $C_{27}H_{31}BMoN_6O_5$ ($[M]^+$): 628.1498. Found: 628.1519.

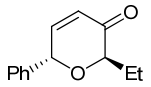


142c

(±)-Dicarbonyl[hydridotris(1-pyrazolyl)borato][(2*R*,3*S*,6*R*)-η-(3,4,5)-2-benzyl-6-mesityl-3-methoxy-3,6-dihydro-2*H*-pyran-3-yl]molybdenum, (±)-142c.

Following the *general procedure,* **138c** (20 mg, 0.029 mmol, 1 equiv) was dissolved in CH_2Cl_2 (1 mL) at 0 ºC, and reacted with HBF_4 (6.1 μL, 0.044 mmol, 1.5 equiv) followed by addition of $NaCNBH_3$ (1.0 M in THF, 117 μL, 0.117 mmol, 4 equiv). Purification by column chromatography on silica gel (hexanes-EtOAc 3:1) afforded (±)-**142c** (17 mg, 85%) as an orange solid

(±)-**142c**: TLC (R_f = 0.40, hexanes-EtOAc 3:1). IR (cm^{-1}): 3007 (w), 2968 (w), 2934 (w), 2482 (w), 1918 (s), 1826 (s), 1505 (m), 1409 (m), 1305 (m). ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.38 (d, *J* = 1.6 Hz, 1H), 7.91 (d, *J* = 2.04 Hz, 1H), 7.69 (d, *J* = 2.0 Hz, 1H), 7.64 (d, *J* = 2.4 Hz, 1H), 7.52 (d, *J* = 2.0 Hz, 2H), 7.17-7.07 (m, 5H), 6.75 (s, 2H), 6.23 (m, 3H), 5.36 (d, *J* = 1.2 Hz, 1H), 4.39 (dd, *J* = 8.0, 1.2 Hz, 1H), 4.14(dd, *J* = 8.8, 4.4 Hz, 1H), 4.05 (d, *J* = 8.0 Hz, 1H), 3.42 (d, *J* = 8.8 Hz, 1H), 3.41 (d, *J* = 4.4 Hz, 1H), 2.87 (s, 3H), 2.48 (s, 6H), 2.22 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 233.3, 230.0, 146.1, 145.3, 141.5, 139.41, 139.37, 138.2, 136.8, 136.2, 135.6, 134.6, 134.0, 130.4 (2), 129.5 (2), 127.7 (2), 125.5, 105.7, 105.6 (2), 72.4, 72.2, 64.3, 57.7, 54.4, 35.5, 23.2 (2), 20.6, 14.1. HRMS(ESI) Calcd for $C_{33}H_{35}BMoN_6O_4$ ($[M]^+$): 688.1861. Found: 688.1867.



143

(±)-(2*R*,6*S*)-2-Ethyl-6-phenyl-6*H*-pyran-3-one, (±)-143.

To a solution of molybdenum complex (±)-**142a** (85 mg, 0.15 mmol, 1.0 equiv) in THF/H_2O (3:1, 6 mL) was added Et_3N (31 μL, 0.22 mmol, 1.5 equiv) at 0 ^oC. Then a solution of ceric ammonium nitrate (640 mg, 1.17 mmol, 8.0 equiv) in water (3 mL) was added dropwise over 5 min. Upon addition, the orange solution changed to light yellow. The reaction was allowed to stir at room temperature for 10 minutes, and then partitioned between CH_2Cl_2 (20 mL) and water (20 mL). The organic layers were collected and washed with brine, dried over $MgSO_4$, concentrated and purified by column

chromatography on silica gel (hexanes-CH_2Cl_2 1:1) to afford (±)-**143** as a colorless oil (13 mg, 44%).

(±)-**143**: TLC (R_f = 0.68, hexanes-EtOAc 2:1). IR (cm^{-1}): 2968 (m), 2934 (m), 1687 (s), 1445 (m), 1386 (m), 1262 (m), 1065 (m). ^1H NMR (400 MHz, $CDCl_3$): δ 7.42-7.34 (m, 5H), 7.13 (dd, *J* = 10.4, 2.8 Hz, 1H), 6.21 (dd, *J* = 10.4, 2.0 Hz, 1H), 5.48 (t, *J* = 2.4 Hz, 1H), 4.05 (dd, *J* = 8.0, 5.2 Hz, 1H), 1.89-1.79 (m, 2H), 1.02 (t, *J* = 7.2 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 196.6, 149.2, 137.3, 128.8 (2C), 128.7, 127.8 (2C), 126.2, 78.6, 72.1, 22.6, 9.9. HRMS (ESI) Calcd for $C_{13}H_{15}O_2$ ($[M+H]^+$): 203.1067. Found: 203.1065.

X-Ray Crystallographic Study:

A suitable crystal of (±)-**142a** was coated with Paratone N oil, suspended in a small fiber loop and placed in a cooled nitrogen gas stream at 173 K on a Bruker D8 APEX II CCD sealed tube diffractometer with graphite monochromated CuK_α (1.54178 Å) radiation. Data were measured using a series of combinations of phi and omega scans with 10 s frame exposures and 0.5^o frame widths. Data collection, indexing and initial cell refinements were all carried out using APEX II[106] software. Frame integration and final cell refinements were done using SAINT[107] software. The final cell parameters were determined from least-squares refinement on 6486 reflections.

[106] APEX II, **2005**, Bruker AXS, Inc., Analytical X-ray Systems, 5465 East Cheryl Parkway, Madison WI 53711-5373.
[107] SAINT Version 6.45A, **2003**, Bruker AXS, Inc., Analytical X-ray Systems, 5465 East Cheryl Parkway, Madison WI 53711-5373.

The structure was solved using Direct methods and difference Fourier techniques (SHELXTL, V6.12).[108] Hydrogen atoms were placed their expected chemical positions using the HFIX command and were included in the final cycles of least squares with isotropic U_{ij} 's related to the atom's ridden upon. Only the Mo and O atoms were refined anisotropically. Scattering factors and anomalous dispersion corrections are taken from the *International Tables for X-ray Crystallography*.[109] Structure solution, refinement, graphics and generation of publication materials were performed by using SHELXTL, V6.12 software. Additional details of data collection and structure refinement are given in Table 13.

Table 13. Crystal data and structure refinement for (±)-142a

Identification code	(±)-**142a**	
Empirical formula	C25 H27 B Mo N6 O4	
Formula weight	582.28	
Temperature	173(2) K	
Wavelength	1.54178 Å	
Crystal system	Triclinic	
Space group	P1	
Unit cell dimensions	a = 8.9047(5) Å	α= 83.821(3)°.
	b = 9.2012(6) Å	β= 77.038(3)°.
	c = 16.2022(9) Å	γ = 88.191(4)°.
Volume	1286.13(13) Å^3	
Z	2	
Density (calculated)	1.504 Mg/m^3	

[108] SHELXTL V6.12, **2002**, Bruker AXS, Inc., Analytical X-ray Systems, 5465 East Cheryl Parkway, Madison WI 53711-5373.
[109] A. J. C. Wilson (ed), *International Tables for X-ray Crystallography, Volume C.* Kynoch, Academic Publishers, Dordrecht, **1992**, Tables 6.1.1.4 (pp. 500-502) and 4.2.6.8 (pp. 219-222).

Absorption coefficient	4.535 mm^{-1}
F(000)	596
Crystal size	0.15 x 0.10 x 0.08 mm^3
Theta range for data collection	2.81 to 61.16°.
Index ranges	-10<=h<=10, -10<=k<=9, -18<=l<=18
Reflections collected	11088
Independent reflections	5379 [R(int) = 0.0218]
Completeness to theta = 61.16°	90.7 %
Absorption correction	Semi-empirical from equivalents
Max. and min. transmission	0.7130 and 0.5495
Refinement method	Full-matrix least-squares on F^2
Data / restraints / parameters	5379 / 3 / 329
Goodness-of-fit on F^2	1.039
Final R indices [I>2sigma(I)]	R1 = 0.0349, wR2 = 0.0865
R indices (all data)	R1 = 0.0378, wR2 = 0.0896
Absolute structure parameter	0.498(19)
Largest diff. peak and hole	0.697 and -0.536 e.$Å^{-3}$

Table 14. Atomic coordinates (x 10^4) and equivalent isotropic displacement parameters ($Å^2$x 10^3) for (±)-142a. U(eq) is defined as one third of the trace of the orthogonalized U^{ij} tensor.

	x	y	z	U(eq)
B(1)	-419(15)	8172(17)	802(9)	31(3)
C(1)	-1079(11)	6261(12)	2933(6)	41(3)
C(2)	-1786(11)	7549(11)	3160(6)	42(2)
C(3)	-1760(13)	8307(15)	2423(7)	39(3)
C(4)	-1607(11)	4973(12)	-53(6)	29(2)
C(5)	-2460(9)	5972(10)	-453(5)	26(2)
C(6)	-2169(11)	7280(12)	-178(6)	31(2)

C(7)	3461(12)	6803(13)	80(7)	25(2)
C(8)	3717(12)	8168(13)	-284(7)	30(3)
C(9)	2388(11)	8923(13)	-23(6)	30(3)
C(10)	-789(13)	3073(15)	1439(7)	32(3)
C(11)	1685(10)	3463(11)	294(6)	17(2)
C(12)	2170(9)	4252(10)	2215(5)	26(2)
C(13)	906(12)	3129(13)	2394(6)	27(2)
C(14)	1481(13)	1545(15)	2249(7)	35(3)
C(15)	3844(12)	2466(12)	1534(6)	34(3)
C(16)	3425(9)	4013(10)	1633(5)	18(2)
C(17)	5111(13)	2459(13)	620(7)	37(3)
C(18)	5698(9)	737(10)	693(5)	42(2)
C(19)	4604(12)	6233(12)	1815(6)	45(3)
C(20)	2119(7)	798(6)	3024(3)	44(3)
C(21)	1760(7)	1341(6)	3814(4)	42(2)
C(22)	2320(8)	641(7)	4489(3)	52(3)
C(23)	3239(8)	-602(7)	4374(3)	47(3)
C(24)	3599(7)	-1145(6)	3585(3)	55(2)
C(25)	3039(7)	-445(6)	2910(3)	49(2)
B(1B)	9401(14)	4524(15)	7072(9)	26(3)
C(1B)	5498(14)	5770(15)	7873(8)	35(3)
C(2B)	5292(13)	4306(14)	8207(7)	37(3)
C(3B)	6703(12)	3643(14)	7893(7)	37(3)
C(4B)	10588(11)	7474(12)	8033(6)	29(2)
C(5B)	11411(10)	6355(10)	8400(6)	31(2)
C(6B)	11087(10)	5132(11)	8082(6)	26(2)
C(7B)	10352(10)	6560(11)	4998(5)	32(2)
C(8B)	11117(10)	5247(11)	4784(6)	39(2)
C(9B)	10645(12)	4186(15)	5525(7)	35(3)
C(10B)	7383(14)	9087(15)	7628(8)	40(3)
C(11B)	9681(14)	9547(15)	6522(7)	33(3)
C(12B)	7108(9)	8427(9)	5627(5)	21(2)
C(13B)	8158(13)	9537(14)	5551(8)	36(3)
C(14B)	7527(14)	11040(15)	5636(8)	35(3)
C(15B)	5015(11)	10142(12)	6504(6)	28(2)
C(16B)	5726(13)	8619(14)	6217(7)	43(3)

C(17B)	3955(15)	10328(15)	7261(8)	49(3)
C(18B)	3142(9)	11602(9)	7496(5)	38(2)
C(19B)	4636(12)	6368(12)	6013(6)	43(3)
C(20B)	7023(7)	11799(6)	4866(3)	33(2)
C(21B)	6597(7)	13260(6)	4909(3)	52(2)
C(22B)	6038(8)	14026(6)	4252(4)	65(2)
C(23B)	5905(9)	13331(7)	3552(3)	71(4)
C(24B)	6331(8)	11870(7)	3509(3)	47(2)
C(25B)	6890(7)	11104(5)	4166(4)	44(2)
Mo(1)	716(1)	4666(1)	1204(1)	24(1)
Mo(1B)	8258(1)	7952(1)	6731(1)	24(1)
N(1)	-629(10)	6266(11)	2106(6)	28(2)
N(2)	-800(9)	7679(10)	1792(5)	28(2)
N(3)	-855(10)	5687(11)	452(5)	28(2)
N(4)	-1183(9)	7089(10)	357(5)	19(2)
N(5)	2064(9)	6642(10)	511(5)	27(2)
N(6)	1364(10)	7980(11)	517(5)	26(2)
N(1B)	6956(9)	5982(9)	7347(5)	21(2)
N(2B)	7648(10)	4614(12)	7439(6)	31(2)
N(3B)	9827(9)	7021(10)	7534(5)	20(2)
N(4B)	10164(11)	5515(12)	7551(6)	34(2)
N(5B)	9494(10)	6369(12)	5826(6)	32(2)
N(6B)	9921(9)	4999(11)	6144(5)	28(2)
O(1)	-1593(12)	2062(11)	1504(6)	50(3)
O(2)	1979(10)	2851(11)	-277(5)	41(2)
O(3)	2623(9)	1527(8)	1533(5)	32(2)
O(4)	4588(10)	4927(10)	1466(5)	40(2)
O(1B)	6889(10)	9841(10)	8208(5)	34(2)
O(2B)	10511(11)	10502(12)	6448(7)	52(3)
O(3B)	6265(9)	11096(10)	6424(5)	36(2)
O(4B)	4430(9)	7667(10)	6483(6)	40(2)

Table 15. Bond lengths [Å] and angles [°] for (±)-142a

B(1)-N(4)	1.546(18)	C(20)-C(25)	1.3900
B(1)-N(6)	1.561(16)	C(21)-C(22)	1.3900
B(1)-N(2)	1.582(16)	C(22)-C(23)	1.3900
C(1)-N(1)	1.309(12)	C(23)-C(24)	1.3900
C(1)-C(2)	1.371(14)	C(24)-C(25)	1.3900
C(2)-C(3)	1.312(15)	B(1B)-N(6B)	1.492(16)
C(3)-N(2)	1.347(15)	B(1B)-N(4B)	1.525(18)
C(4)-C(5)	1.375(13)	B(1B)-N(2B)	1.543(15)
C(4)-N(3)	1.392(14)	C(1B)-N(1B)	1.390(14)
C(5)-C(6)	1.379(14)	C(1B)-C(2B)	1.399(18)
C(6)-N(4)	1.361(13)	C(2B)-C(3B)	1.393(16)
C(7)-N(5)	1.287(13)	C(3B)-N(2B)	1.295(15)
C(7)-C(8)	1.333(16)	C(4B)-N(3B)	1.274(14)
C(8)-C(9)	1.359(15)	C(4B)-C(5B)	1.403(14)
C(9)-N(6)	1.370(14)	C(5B)-C(6B)	1.351(14)
C(10)-O(1)	1.173(15)	C(6B)-N(4B)	1.332(14)
C(10)-Mo(1)	1.966(13)	C(7B)-N(5B)	1.383(12)
C(11)-O(2)	1.111(13)	C(7B)-C(8B)	1.406(13)
C(11)-Mo(1)	1.966(9)	C(8B)-C(9B)	1.456(15)
C(12)-C(16)	1.321(12)	C(9B)-N(6B)	1.349(15)
C(12)-C(13)	1.509(15)	C(10B)-O(1B)	1.222(15)
C(12)-Mo(1)	2.299(8)	C(10B)-Mo(1B)	1.891(12)
C(13)-C(14)	1.554(17)	C(11B)-O(2B)	1.146(16)
C(13)-Mo(1)	2.299(11)	C(11B)-Mo(1B)	1.922(14)
C(14)-O(3)	1.361(13)	C(12B)-C(13B)	1.384(16)
C(14)-C(20)	1.577(13)	C(12B)-C(16B)	1.397(14)
C(15)-O(3)	1.411(14)	C(12B)-Mo(1B)	2.250(7)
C(15)-C(16)	1.476(14)	C(13B)-C(14B)	1.485(18)
C(15)-C(17)	1.649(14)	C(13B)-Mo(1B)	2.293(12)
C(16)-O(4)	1.316(12)	C(14B)-O(3B)	1.504(13)
C(17)-C(18)	1.653(14)	C(14B)-C(20B)	1.513(13)
C(19)-O(4)	1.384(14)	C(15B)-C(17B)	1.393(15)
C(20)-C(21)	1.3900	C(15B)-O(3B)	1.414(14)

C(15B)-C(16B)	1.592(16)	O(2)-C(11)-Mo(1)	166.3(9)
C(16B)-O(4B)	1.430(15)	C(16)-C(12)-C(13)	117.6(9)
C(17B)-C(18B)	1.401(15)	C(16)-C(12)-Mo(1)	91.9(5)
C(19B)-O(4B)	1.470(13)	C(13)-C(12)-Mo(1)	70.8(5)
C(20B)-C(21B)	1.3900	C(12)-C(13)-C(14)	114.4(9)
C(20B)-C(25B)	1.3900	C(12)-C(13)-Mo(1)	70.8(5)
C(21B)-C(22B)	1.3900	C(14)-C(13)-Mo(1)	116.8(7)
C(22B)-C(23B)	1.3900	O(3)-C(14)-C(13)	111.2(10)
C(23B)-C(24B)	1.3900	O(3)-C(14)-C(20)	108.1(9)
C(24B)-C(25B)	1.3900	C(13)-C(14)-C(20)	111.4(9)
Mo(1)-N(3)	2.182(9)	O(3)-C(15)-C(16)	116.2(8)
Mo(1)-N(5)	2.258(9)	O(3)-C(15)-C(17)	108.8(8)
Mo(1)-N(1)	2.303(9)	C(16)-C(15)-C(17)	106.2(8)
Mo(1B)-N(3B)	2.208(8)	O(4)-C(16)-C(12)	120.6(9)
Mo(1B)-N(1B)	2.202(8)	O(4)-C(16)-C(15)	115.5(8)
Mo(1B)-N(5B)	2.262(10)	C(12)-C(16)-C(15)	116.1(9)
N(1)-N(2)	1.361(13)	C(15)-C(17)-C(18)	100.1(8)
N(3)-N(4)	1.314(13)	C(21)-C(20)-C(25)	120.0
N(5)-N(6)	1.362(13)	C(21)-C(20)-C(14)	121.5(6)
N(1B)-N(2B)	1.393(14)	C(25)-C(20)-C(14)	118.5(6)
N(3B)-N(4B)	1.407(14)	C(20)-C(21)-C(22)	120.0
N(5B)-N(6B)	1.384(14)	C(23)-C(22)-C(21)	120.0
		C(24)-C(23)-C(22)	120.0
N(4)-B(1)-N(6)	107.9(10)	C(25)-C(24)-C(23)	120.0
N(4)-B(1)-N(2)	108.6(10)	C(24)-C(25)-C(20)	120.0
N(6)-B(1)-N(2)	104.6(9)	N(6B)-B(1B)-N(4B)	107.7(10)
N(1)-C(1)-C(2)	112.0(9)	N(6B)-B(1B)-N(2B)	115.7(9)
C(3)-C(2)-C(1)	103.0(9)	N(4B)-B(1B)-N(2B)	106.9(10)
C(2)-C(3)-N(2)	110.5(11)	N(1B)-C(1B)-C(2B)	110.8(11)
C(5)-C(4)-N(3)	109.3(9)	C(3B)-C(2B)-C(1B)	104.2(11)
C(4)-C(5)-C(6)	103.6(8)	N(2B)-C(3B)-C(2B)	109.5(11)
N(4)-C(6)-C(5)	111.1(9)	N(3B)-C(4B)-C(5B)	112.9(10)
N(5)-C(7)-C(8)	111.5(10)	C(6B)-C(5B)-C(4B)	104.9(8)
C(7)-C(8)-C(9)	106.1(9)	N(4B)-C(6B)-C(5B)	107.6(9)
C(8)-C(9)-N(6)	107.7(10)	N(5B)-C(7B)-C(8B)	109.6(9)
O(1)-C(10)-Mo(1)	172.9(10)	C(7B)-C(8B)-C(9B)	106.1(8)

N(6B)-C(9B)-C(8B)	104.0(10)	N(5)-Mo(1)-C(12)	94.8(3)
O(1B)-C(10B)-Mo(1B)	176.8(11)	C(10)-Mo(1)-C(13)	67.9(4)
O(2B)-C(11B)-Mo(1B)	175.9(11)	C(11)-Mo(1)-C(13)	101.0(4)
C(13B)-C(12B)-C(16B)	114.0(9)	N(3)-Mo(1)-C(13)	145.1(3)
C(13B)-C(12B)-Mo(1B)	74.0(6)	N(5)-Mo(1)-C(13)	133.2(4)
C(16B)-C(12B)-Mo(1B)	88.0(6)	C(12)-Mo(1)-C(13)	38.3(4)
C(12B)-C(13B)-C(14B)	117.0(10)	C(10)-Mo(1)-N(1)	99.1(4)
C(12B)-C(13B)-Mo(1B)	70.6(6)	C(11)-Mo(1)-N(1)	170.4(4)
C(14B)-C(13B)-Mo(1B)	120.9(8)	N(3)-Mo(1)-N(1)	78.5(3)
C(13B)-C(14B)-O(3B)	111.6(10)	N(5)-Mo(1)-N(1)	85.7(3)
C(13B)-C(14B)-C(20B)	115.9(10)	C(12)-Mo(1)-N(1)	84.2(3)
O(3B)-C(14B)-C(20B)	110.7(9)	C(13)-Mo(1)-N(1)	87.7(3)
C(17B)-C(15B)-O(3B)	108.8(9)	C(10B)-Mo(1B)-C(11B)	78.5(5)
C(17B)-C(15B)-C(16B)	125.4(10)	C(10B)-Mo(1B)-N(3B)	87.1(4)
O(3B)-C(15B)-C(16B)	106.9(8)	C(11B)-Mo(1B)-N(3B)	81.8(4)
C(12B)-C(16B)-O(4B)	129.0(11)	C(10B)-Mo(1B)-N(1B)	93.5(5)
C(12B)-C(16B)-C(15B)	125.8(11)	C(11B)-Mo(1B)-N(1B)	160.9(4)
O(4B)-C(16B)-C(15B)	102.4(8)	N(3B)-Mo(1B)-N(1B)	80.4(3)
C(18B)-C(17B)-C(15B)	127.7(11)	C(10B)-Mo(1B)-C(12B)	111.3(4)
C(21B)-C(20B)-C(25B)	120.0	C(11B)-Mo(1B)-C(12B)	100.8(4)
C(21B)-C(20B)-C(14B)	115.9(6)	N(3B)-Mo(1B)-C(12B)	161.7(3)
C(25B)-C(20B)-C(14B)	124.0(6)	N(1B)-Mo(1B)-C(12B)	98.3(3)
C(20B)-C(21B)-C(22B)	120.0	C(10B)-Mo(1B)-N(5B)	170.1(5)
C(21B)-C(22B)-C(23B)	120.0	C(11B)-Mo(1B)-N(5B)	102.4(4)
C(22B)-C(23B)-C(24B)	120.0	N(3B)-Mo(1B)-N(5B)	83.4(3)
C(25B)-C(24B)-C(23B)	120.0	N(1B)-Mo(1B)-N(5B)	82.5(3)
C(24B)-C(25B)-C(20B)	120.0	C(12B)-Mo(1B)-N(5B)	78.3(3)
C(10)-Mo(1)-C(11)	80.8(5)	C(10B)-Mo(1B)-C(13B)	102.1(5)
C(10)-Mo(1)-N(3)	82.8(4)	C(11B)-Mo(1B)-C(13B)	65.3(5)
C(11)-Mo(1)-N(3)	92.0(4)	N(3B)-Mo(1B)-C(13B)	142.8(4)
C(10)-Mo(1)-N(5)	158.9(4)	N(1B)-Mo(1B)-C(13B)	133.7(4)
C(11)-Mo(1)-N(5)	91.1(4)	C(12B)-Mo(1B)-C(13B)	35.4(4)
N(3)-Mo(1)-N(5)	78.0(3)	N(5B)-Mo(1B)-C(13B)	87.1(4)
C(10)-Mo(1)-C(12)	106.1(4)	C(1)-N(1)-N(2)	104.8(9)
C(11)-Mo(1)-C(12)	105.1(3)	C(1)-N(1)-Mo(1)	135.0(8)
N(3)-Mo(1)-C(12)	161.7(3)	N(2)-N(1)-Mo(1)	118.8(6)

C(3)-N(2)-N(1)	105.7(8)	C(3B)-N(2B)-B(1B)	130.6(11)
C(3)-N(2)-B(1)	128.9(10)	N(1B)-N(2B)-B(1B)	116.6(9)
N(1)-N(2)-B(1)	121.8(9)	C(4B)-N(3B)-N(4B)	104.1(9)
N(4)-N(3)-C(4)	108.3(9)	C(4B)-N(3B)-Mo(1B)	137.6(8)
N(4)-N(3)-Mo(1)	126.0(7)	N(4B)-N(3B)-Mo(1B)	118.3(7)
C(4)-N(3)-Mo(1)	125.6(7)	C(6B)-N(4B)-N(3B)	110.4(9)
N(3)-N(4)-C(6)	107.6(9)	C(6B)-N(4B)-B(1B)	128.0(10)
N(3)-N(4)-B(1)	119.8(9)	N(3B)-N(4B)-B(1B)	121.3(9)
C(6)-N(4)-B(1)	132.6(10)	C(7B)-N(5B)-N(6B)	104.7(8)
C(7)-N(5)-N(6)	108.1(9)	C(7B)-N(5B)-Mo(1B)	132.8(8)
C(7)-N(5)-Mo(1)	132.6(8)	N(6B)-N(5B)-Mo(1B)	119.8(6)
N(6)-N(5)-Mo(1)	119.3(6)	C(9B)-N(6B)-N(5B)	112.7(9)
N(5)-N(6)-C(9)	106.1(8)	C(9B)-N(6B)-B(1B)	127.6(10)
N(5)-N(6)-B(1)	122.4(10)	N(5B)-N(6B)-B(1B)	119.2(9)
C(9)-N(6)-B(1)	127.6(10)	C(14)-O(3)-C(15)	112.2(9)
C(1B)-N(1B)-N(2B)	102.7(9)	C(16)-O(4)-C(19)	125.5(8)
C(1B)-N(1B)-Mo(1B)	133.1(8)	C(15B)-O(3B)-C(14B)	115.9(9)
N(2B)-N(1B)-Mo(1B)	122.8(6)	C(16B)-O(4B)-C(19B)	111.7(8)
C(3B)-N(2B)-N(1B)	112.5(9)		

Symmetry transformations used to generate equivalent atoms:

Table 16. Anisotropic displacement parameters ($Å^2$x 10^3)for (±)-142a. The anisotropic displacement factor exponent takes the form: $-2\pi^2[h^2a^{*2}U^{11} + ... + 2 h k a^* b^* U^{12}]$

	U^{11}	U^{22}	U^{33}	U^{23}	U^{13}	U^{12}
B(1B)	31(4)	11(4)	36(5)	-1(3)	-14(3)	14(3)
Mo(1)	30(1)	20(1)	25(1)	-2(1)	-10(1)	4(1)
Mo(1B)	28(1)	19(1)	26(1)	-2(1)	-10(1)	4(1)
O(1)	64(5)	32(6)	55(6)	17(4)	-24(4)	-24(5)
O(2)	52(5)	35(5)	36(5)	-9(4)	-7(3)	15(4)
O(3)	49(4)	12(4)	44(4)	-12(3)	-29(3)	9(4)
O(4)	43(5)	31(6)	44(5)	6(4)	-7(4)	-2(4)
O(1B)	44(4)	29(5)	33(4)	-8(3)	-14(3)	6(4)

O(2B)	49(5)	51(7)	61(6)	-5(5)	-21(4)	-4(5)
O(3B)	36(4)	37(5)	29(4)	4(3)	4(3)	6(4)
O(4B)	43(5)	29(5)	59(5)	-13(4)	-32(4)	5(4)

Table 17. Hydrogen coordinates (x 10^4) and isotropic displacement parameters ($Å^2$x 10^3) for (±)-142a

	x	y	z	U(eq)
H(1)	-679	9370	634	38
H(1)	-935	5476	3320	50
H(2)	-2186	7819	3703	50
H(3)	-2326	9159	2347	46
H(4)	-1543	3976	-110	35
H(5)	-3085	5805	-822	31
H(6)	-2591	8176	-337	38
H(7)	4199	6061	30	30
H(8)	4622	8532	-644	36
H(9)	2206	9902	-182	36
H(12)	2067	5082	2504	31
H(13)	-130	3366	2576	33
H(14)	615	970	2184	42
H(15)	4347	2087	1994	40
H(17A)	5948	3131	580	45
H(17B)	4635	2691	139	45
H(18A)	6131	450	1178	63
H(18B)	6478	681	181	63
H(18C)	4867	95	696	63
H(19A)	3753	6854	1731	67
H(19B)	5551	6752	1593	67
H(19C)	4503	5948	2412	67
H(21)	1144	2173	3891	51
H(22)	2079	1004	5017	62
H(23)	3614	-1071	4826	56

H(24)	4215	-1977	3508	66
H(25)	3280	-808	2381	59
H(1B)	9763	3463	7225	31
H(1B)	4759	6503	7986	42
H(2B)	4414	3873	8558	44
H(3B)	6930	2656	7994	45
H(4B)	10598	8445	8142	35
H(5B)	12041	6436	8779	38
H(6B)	11444	4193	8211	31
H(7B)	10414	7425	4638	39
H(8B)	11790	5088	4272	47
H(9B)	10805	3179	5564	42
H(12B)	7304	7625	5314	25
H(13B)	9036	9537	5021	43
H(14B)	8371	11626	5720	42
H(15B)	4492	10532	6055	34
H(17C)	3174	9592	7310	59
H(17D)	4496	10034	7710	59
H(18D)	3896	12359	7405	57
H(18E)	2534	11567	8068	57
H(18F)	2484	11802	7102	57
H(19D)	4712	6579	5412	64
H(19E)	3759	5759	6256	64
H(19F)	5554	5870	6109	64
H(21B)	6686	13725	5378	62
H(22B)	5753	15003	4281	78
H(23B)	5531	13843	3112	85
H(24B)	6242	11405	3040	57
H(25B)	7175	10126	4137	52

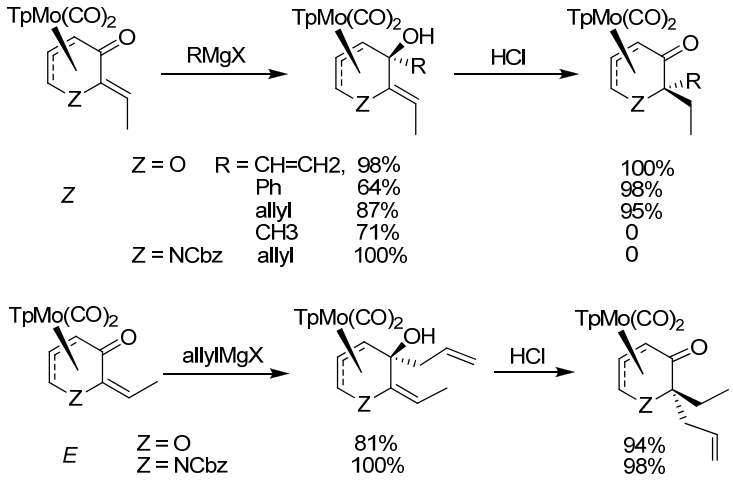
Chapter 4

Toward the Total Synthesis of (-)-Malyngolide

Introduction

Chiral molybdenum complexes can be employed as scaffolds for the asymmetric construction of highly functionalized heterocycles. Several methods have been developed in our lab to build 2,3,6-trisubstituted dihydropyrans [110] and multi-substituted piperidines.[111,112] More recently, our group member Dr. Yongqiang Zhang discovered a new type of reaction of molybdenum complexes. Treatment of allyl hydroxyl molybdenum complexes with HCl resulted in a novel rearrangement reaction, which is called semipinacol rearrangement (Scheme 72).

Scheme 72. Semipinacol Reaction of Pyranyl and Pyridinyl Molybdenum Scaffolds[113]

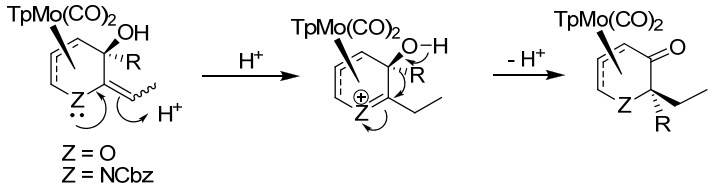


A possible mechanism of the stereoselective semipinacol reaction is shown in Scheme 73. As observed in traditional pinacol rearrangement, R groups that possess the ability to stabilize a carbon cation prefer to rearrange in both pyranyl and pyridinyl molybdenum

[110] Yin, J. J.; Llorente, I.; Villanueva, L. A.; Liebeskind, L. S. *J. Am. Chem. Soc.* **2000**, *122*, 10458-10459.
[111] Shu, C.T.; Alcudia, A.; Yin, J. J.; Liebeskind, L. S. *J. Am. Chem. Soc.* **2001**, *123*, 12477-12487.
[112] Shu, C.T.; Liebeskind, L. S. *J. Am. Chem. Soc*. **2003**, 125, 2878-2879.
[113] Dr. Yongqiang Zhang, Liebeskind's group research report, Emory University.

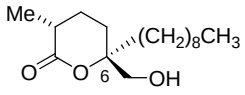
complexes. This rearrangement provides an innovative extension of the synthetic power of molybdenum scaffolds in the construction of quaternary carbon centers in both dihydropyran and piperidine rings.

Scheme 73. Possible Mechanism of Semipinacol Rearrangement



(-)-Malyngolide (Figure 10) is a naturally occurring δ-lactonic compound, which was isolated from marine algae and exhibits antibiotic activity against pathogenic species of *Mycobacterium smegmatis* and *Streptococcus pyngenes*.[114] Since the first paper published by Mukaiyama in 1980,[115] a number of reports have appeared about the total synthesis of (-)-malyngolide.[116] Normally, the quaternary carbon center in (-)-malyngolide was built up by preparation of a stereogenic tertiary alcohol followed by subsequent ring closure[116b,c,e,f,g]. Herein, a synthetic route to (-)-malyngolide was proposed, as shown in Scheme 74, in which the semipinacol rearrangement was utilized as the key transformation to build the chiral quaternary carbon center.

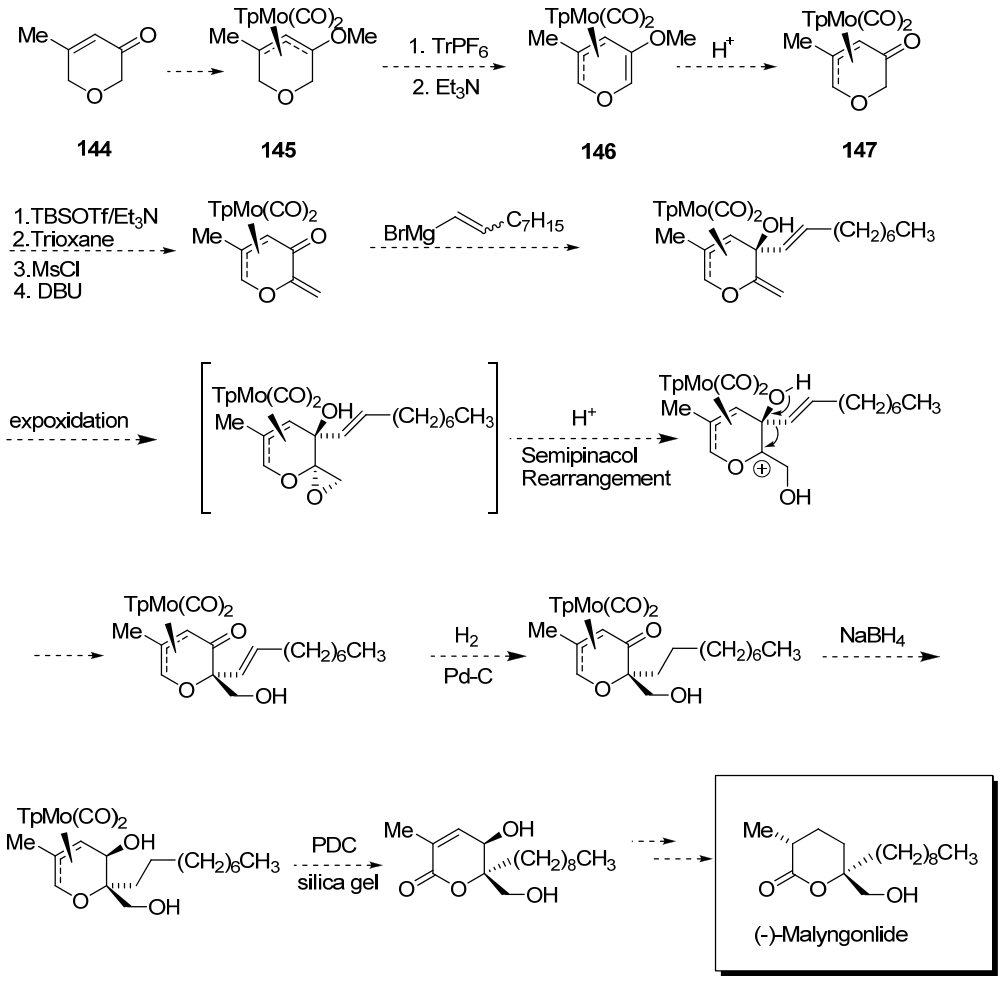
[114] Koumbis, A. E.; Dieti, K. M.; Vikentiu, M. G.; Gallos, J. K. *Tetrahedron Lett.* **2003**, *44*, 2513-2516.
[115] Saktio, Y.; Tanaka, S.; Asami, M.; Mukaiyama, T. *Chem. Lett*. **1980**, 1223-1226.
[116] For recent publications about the total synthesis of (-)-malyngolide, see: (a) Wan, Z. H.; Nelson, S. G. *J. Am. Chem. Soc.* **2000**, *122*, 10470-10471. (b) Trost, B. M.; Tang, W.; Schulte, J. L. *Org. Lett.* **2000**, *2*, 4013-4015. (c) Suzuki, T.; Ohmori, K.; Suzuki, K. *Org. Lett.* **2001**, *3*, 1741-744. (d) Ghosh, A. K.; Shirai, M. *Tetrahedron Lett.* **2001**, *42*, 6231-6233. (e) Mizutani, H.; Watanabe, M.; Honda, T. Tetrahedron, **2002**, *58*, 8929-8936. (f) Carda, M.; Rodríguez, S.; Castillo, E.; Bellido, A.; Díaz-Oltra, S.; Marco, J. A. *Tetrahedron* **2003**, *59*, 857-864. (g) Koumbis, A. E.; Dieeti, K. M.; Vikentiou, M. G.; Gallos, J. K. *Tetrahedron Lett.* **2003**, *44*, 2513-2516.



(-)-malyngonlide

Figure 10. (-)-Malyngolide

Scheme 74. Proposed Synthetic Route to (-)-Malyngolide



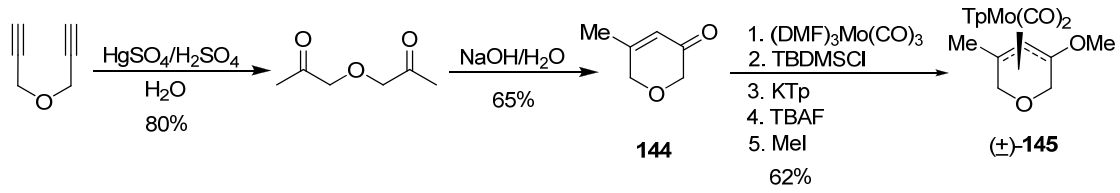
Results and Discussion

The Synthesis of 3-Methyl-5-oxopyranyl Molybdenum Scaffold 147

The synthesis of 3-methyl-5-oxopryanyl scaffold **147** commenced with the preparation of

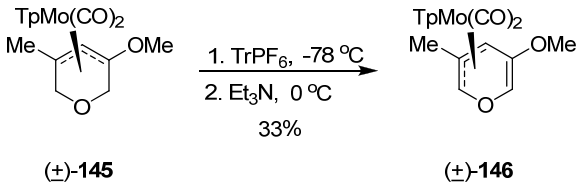
enone **144**,[117] which was synthesized *via* oxymercuration of commercially available propargyl ether followed by intramolecular aldol condensation and dehydration. These reactions gave satisfactory yields as shown in Scheme 75. With enone **144** in hand, molybdenum complex **145** was obtained by metalation of **144** under standard conditions[118] in 62% yield.

Scheme 75. Synthesis of Molybdenum Complex 144



Treatment of complex **145** with solid Ph_3CPF_6 at -78 ^oC followed by addition of Et_3N at 0 ^oC afforded the unsaturated molybdenum complex **146** (Scheme 76). However, as a one-pot reaction, the yield of **146** was relatively low (33%).

Scheme 76. One-pot Synthesis of Molybdenum Complex 146

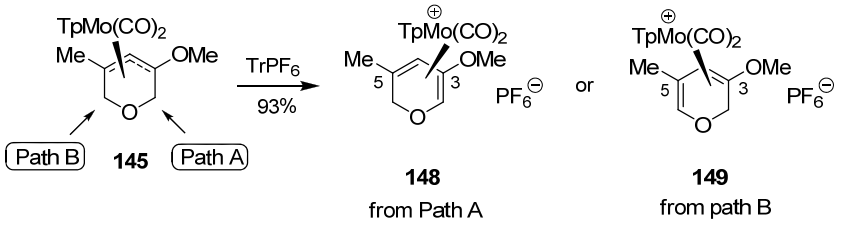


With the intention of increasing the yield, this reaction was carried out in two separate steps. The hydride abstraction of complex **145** gave diene complex in satisfactory yield

[117] Skinnemoen, K.; Undheim, K. *Acta Chem. Scan. B* **1980**, *34*, 295-297.
[118] Ward, Y. D.; Villanueva, L. A.; Allred, G. D.; Liebeskind, L. S. *Organometallics* **1996**, *15*, 4201-4210.

(93%) (Scheme 77). Although there are two possible sites for the hydride abstraction, only one regio-isomer of the cationic diene complex was observed. Attempts to determine the structure of diene by ^{1}H NOE experiment failed to find the desired NOE effect (Figure 11) since the cationic diene complex decomposed very quickly (30 min - 60 min) in CD_2Cl_2 at room temperature.

Scheme 77. Hydride Abstraction of Compound 145



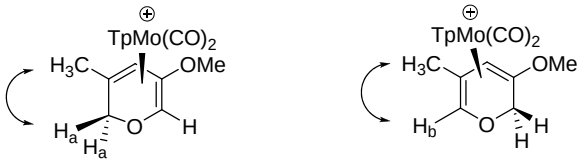


Figure 11. Expected NOE Effects in Cationic Diene 148 and 149

To confirm the structure, a crystal of diene complex suitable for a diffraction study was grown in CH_2Cl_2/hexanes at -10 ^oC.[119] As shown in Figure 12, the structure of cationic diene molybdenum complex was confirmed as compound **148** by the X-ray diffraction study; hence the hydride abstraction went through path A as shown in Scheme 77. The regioselectivity of the hydride abstraction with Ph_3CPF_6 is consistent with the

[119] The diene cyrstal easily decomposed in dichloromethane at room temperature.

observation of Pearson[120] in the hydride abstraction of organoiron π-complexes, which was rationalized by the frontier molecular orbital theory. According to his arguments, the hydride abstraction will place the strongest π-donor[121] in the C-3 position (Scheme 77), and generates the most stable cationic complex.

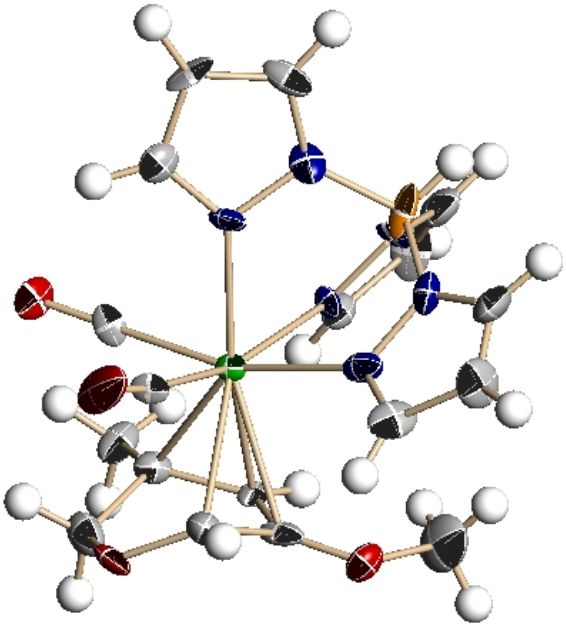
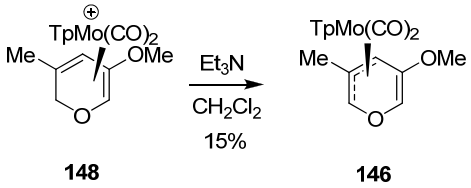


Figure 12. ORTEP View of Cationic Diene (±)-148

Started from diene **148**, the deprotonation only afforded complex **146** in 15% yield (Scheme 78). Different bases (Et_3N, $KOSiMe_3$ and KHMDS) and solvents (acetonitrile, nitromethane, *t*-butyldimethyl ether, diethyl ether) were examined, but none of them improved the yield.

[120] Eisenstein, O.; Butler, W. M.; Pearson, A. J. *Organometallics* **1984**, *3*, 1150-1157.
[121] In our case, the methoxy group is a better π-donor compared to the methyl group.

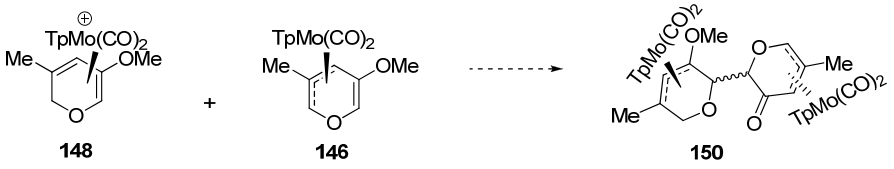
Scheme 78. Synthesis of Molybdenum Complex 146 from Diene 148



148 **146**

During the study of the deprotonation reaction of compound **148**, dimers **150**[122] were isolated from the reaction mixture (Scheme 79). The dimers **150** might derive from the nucleophilic addition of unsaturated molybdenum complex **146** to the diene complex **148**. To avoid the potential dimerization between **146** and **148**, the addition sequence of molybdenum diene complex **148** and different bases was intentionally reversed (addition of a solution of diene **148** into a solution of base). Gratifyingly, the yield was improved to 71% on a 550 mg scale (Table 18, entry 7). Yields of **146** using different bases and solvents are summarized in Table 18.

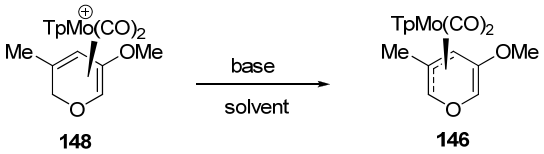
Scheme 79. Possible Route to Dimers 150



148 **146** **150**

[122] The proposed structure of **150** as shown in Scheme 79 is based on its ^{1}H NMR spectra which displayed two sets of proton signals from Tp. IR spectra of **150** also revealed an additional carbonyl absorption peak, which supported this hypothetic structure. However, no further evidence was obtained to verify this hypothesis.

Table 18. Optimization of the Synthesis of Molybdenum Complex 146

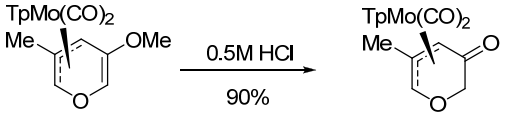


148 146

Entry	Base	Conditions	Solvent	Yield (%)
1	Et_3N	10 equiv	CH_2Cl_2	15
2	$KOSiMe_3$	5 equiv	CH_2Cl_2	19
3	KHMDS	1.2 equiv	CH_2Cl_2	20
4	Et_3N	10 equiv	CH_2Cl_2	48
5	Et_3N	10 equiv	TBME	32
6	Et_3N	10 equiv	Et_2O	34
7	Et_3N	10 equiv (reverse addition)	CH_2Cl_2	71

Finally, treatment of complex **146** with 0.5M HCl in ethanol afforded 3-methyl-5-oxopyranyl scaffold **147** in 90% yield (Scheme 80).

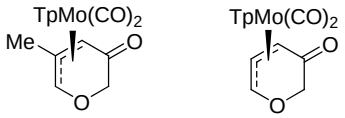
Scheme 80. Synthesis 3-Methyl-5-Oxopyranyl Scaffold 147



146 147

Model Study toward the Synthesis of (-)-Malyngolide

Since 3-methyl-5-oxopyranyl scaffold **147** and 5-oxopyranyl scaffold **86** (Figure 13) share a similar pyranyl skeleton with a carbonyl group at C-5, molybdenum complex **86** was chosen to carry out the model study toward the synthesis of (-)-malyngolide.

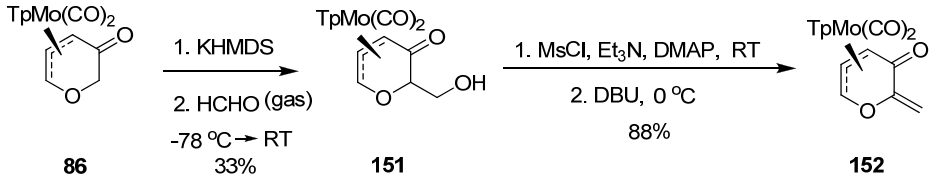


147 86

Figure 13. Molybdenum Complexes 86 and 147

Conversion of 5-oxopyranyl complex **86** to hydroxyl complex **151** was accomplished by an aldol reaction and subsequent mesylation and dehydration (Scheme 81). Although the dehydration gave a high yield of complex **152**, the yield of the aldol reaction was only 33%. This result might due to the poor solubility of paraformaldehyde in THF. Even if the HCHO gas was introduced to this reaction, at -78 ^{o}C the gas HCHO easily solidified again.

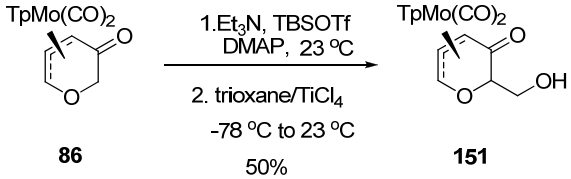
Scheme 81. Synthesis of Enone 152



86 **151** **152**

Compared to traditional aldol reaction, the Mukaiyam-aldol reaction of complex **86** with trioxane afforded **151** in higher yield (50%) (Scheme 82).

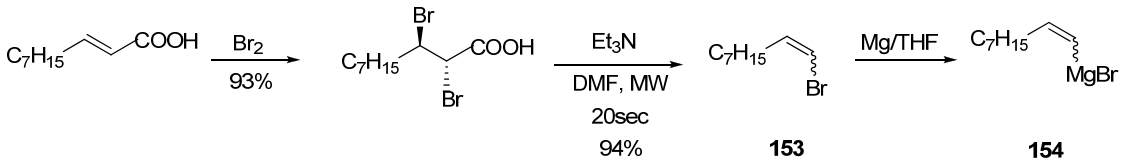
Scheme 82. Mukaiyama-aldol Reaction of Complex 86 with Trioxane



86 **151**

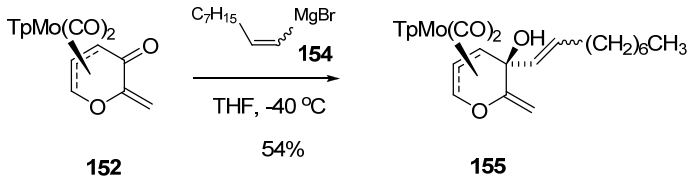
The nine carbon Grignard reagent needed for the synthesis of (-)-malyngolide was obtained from the vinyl bromide **153**. Compound **153** was prepared following a literature procedure.[123] As can be seen from Scheme 83, 2,3-dibromo carboxylic acid was readily prepared by bromination of the *trans*-2-decenoic acid in CH_2Cl_2. Microwave irradiation (20 seconds) of *anti*-2,3 dibromoalkanoic acid in DMF, in the presence of 1.05 equiv of triethylamine, gave the corresponding vinyl bromide **153** as a mixture of both *Z* and *E* isomers in excellent yields.

Scheme 83. Synthesis of Grignard Reagent 154



Addition of Grignard reagent **154** to compound **152** gave a moderate yield of the tertiary alcohol **155** (54%) (Scheme 84).

Scheme 84. Synthesis of Complex 155



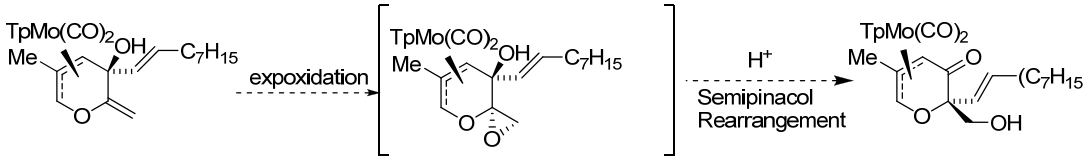
Attempts to Carry out the Key Semipinacol Rearrangement

In the proposed synthetic route to (-)-malyngolide, the epoxidation induced semipinacol

[123] Kuang, C. X.; Senboku, H.; Tokuda, M. *Tetrahedron Lett*. **2001**, *42*, 3893-3896.

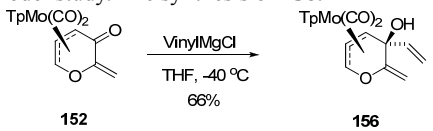
reaction was expected not only to introduce the quaternary carbon center, but also to install the requisite hydroxyl group (Scheme 85). Epoxidation should take place at the more electron-rich exocyclic double bond, and generate a cationic intermediate which would initiate the semipinacol rearrangement.

Scheme 85. Proposed Epoxidation-induced Semipinacol Reaction



Unfortunately, the model study of complex **156** [124] with *m*-CPBA and *tert*-butyl hydroperoxide in the presence of vanadyl acetylacetonate[125] only afforded the recovered starting material and possible demetalation products (Scheme 86). Also, no epoxide formation was observed. Similar to epoxidation, dihydroxylation with commercially available AD-mix-β (with or without of $MeSO_2NH_2$) [126] only led to the recovery of the starting material.

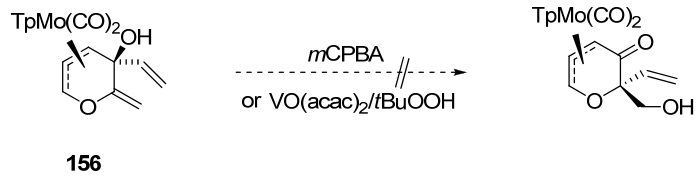
[124] Complex **156** was employed for model study. The synthesis of **156**:



152 **156**

[125] Sharpless, K. B.; Michaelson, R. C. *J. Am. Chem. Soc.* **1973**, *95*, 6136-6137.
[126] Kolb, H. C.; VanNieuwenhze, M. S.; Sharpless, K. B. *Chem. Rev.* **1994**, *94*, 2483-2547.

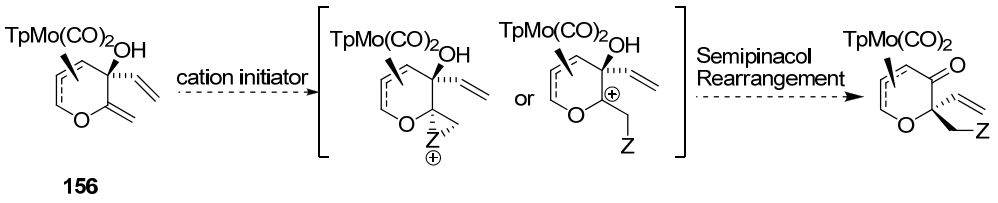
Scheme 86. Epoxidation of Complex 156



156

Since attempts to directly introduce a hydroxyl group by semipinacol rearrangement were not successful, other electrophiles that would react with the double bond through a cationic or bridged cationic intermediate and introduce a heteroatom were examined (Scheme 87). These electrophiles included [bis(acetoxy)iodo]benzene, 4-nitrobenzenesulfenyl chloride, mercury acetate (oxymercuration) and iodine-silver trifluoroacetate.

Scheme 87. Attempts to Semipinacol Reaction



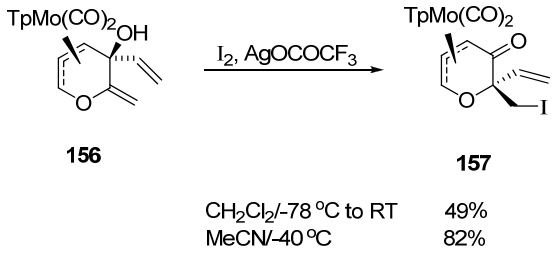
156

Among these efforts, only iodine-silver trifluoroacetate successfully initiated the semipinacol rearrangement of complex **156**, and provided the desired semipinacol adduct **157** in 49% yield in CH_2Cl_2 (Scheme 88). In this reaction, the combination of iodine and $AgOCOCF_3$ generates electrophilic iodine trifluoroacetate ($IOCOCF_3$) as the reactive iodine source. According to the observation of Lipshutz,[127] solvents played a major role in the efficiency of reactions between allylic alcohols and $IOCOCF_3$. Acetonitrile is the

[127] Lipshutz, B. H; Barton, J. C. *J. Am. Chem. Soc.* **1992**, *114,* 1084-1086.

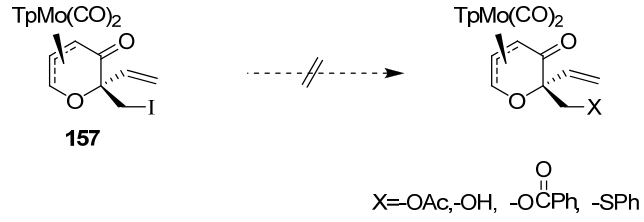
most efficient solvent of those examined. Hence, the solvent was changed from dichloromethane to acetonitrile, and the yield was improved dramatically. The best yield of complex **157** achieved was 82%.

Scheme 88. $IOCOCF_3$ Induced Semipinacol Rearrangement



Efforts to transfer the iodine in complex **157** to an acetoxyl group, a hydroxyl group and a benzoyloxyl group failed to give the substitution product under various conditions (Scheme 89). The low reactivity of nucleophilic substitution might come from steric hindrance of the iodide which is adjacent to a quaternary carbon center.

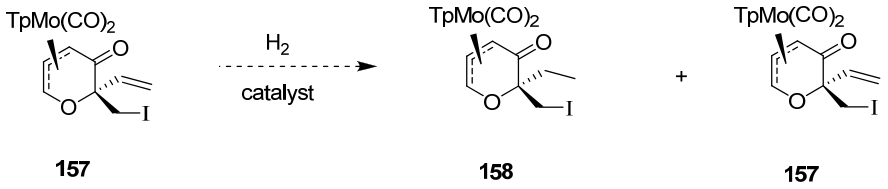
Scheme 89. Attempts to Substitute Iodine in Complex 157



Catalytic hydrogenation to reduce the double bond in complex **157** (Scheme 90) using different catalysts including Pd/C, $Pd(OH)_2/C$,PtO_2, $RhCl(PPh_3)_3$ were probed, but all of them gave a mixture of **157** and **158**. Since complexes **157** and **158** are inseparable by

simple silica gel chromatography, hydrogenation conditions still need to be optimized.

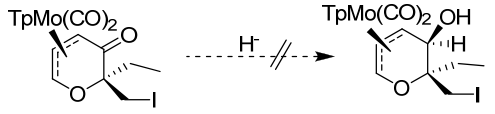
Scheme 90. Catalytic Hydrogenation of Complex 157



157 **158** **157**

Finally, all attempts to reduce the carbonyl group in complex **158** were also fruitless (Scheme 91). When complex **158** was treated with $NaBH_4$, starting materials could be recovered, and decomposition was observed. Whereas when **158** was treated with $LiAlH_4$ or $_L$-Selectride, the reaction mixture was easily decomposed on the rotary evaporator.[128]

Scheme 91. Hydride Addition of Complex 158



158 **159**

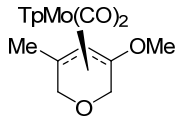
Conclusion

Racemic 3-methyl-5-oxopyranyl molybdenum complex **147** was prepared from commercially available propargyl ether in six steps. As a model study, through a Mukaiyama-aldol reaction and the subsequent dehydration, an exocyclic double bond was introduced to afford 5-oxopyranyl molybdenum complex **86**. The nucleophilic

[128] Hydride addition might go through a 1,5-Michael reaction pathway instead of 1,2 addition. For a similar example, see Chapter 3, Scheme 50.

addition of the 9-carbon aliphatic Grignard reagent **154** to enone **152** gave the desired molybdenum diene **155**. Iodine-silver trifluoroacetate successfully initiated the semipinacol rearrangement of complex **156**. However, further attempts to manipulate complex **156** towards (-)-malyngolide were not successful.

Experimental Section



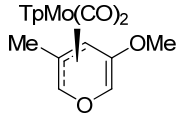
145

(±)-Dicarbonyl[hydridotris(1-pyrazolyl)borato][(2*S*,3*R*)-η-(3,4,5)-3-methoxyl-5-methyl-3,6-dihydro-2*H*-pyran-3-yl]molybdenum, (±)-145.

In a Schlenk flask, $(DMF)_3Mo(CO)_3$ (1.7 g, 26.8 mmol, 1.2 equiv) was dissolved in dry, degassed CH_2Cl_2 (100 mL) at room temperature. To this solution, a solution of 5-methyl-2*H*-pyran-3-one (2.5 g, 22.3 mmol, 1 equiv) in CH_2Cl_2 (10 mL) was added. After being stirred for 30 min, TBDMSCl (3.7 g, 24.5 mmol, 1.1 equiv) was added. The reaction was stirred overnight at 25 ^oC, at which time solid KTp (5.7 g, 22.3 mmol, 1 equiv) was added to the solution. After 1 h, TBAF (14.6 g, 55.8 mmol, 2.5 equiv) was added to reaction, and stirred for 30 min. Then MeI (63.3 g, 0.45 mol, 20 equiv) was added to reaction. After being stirred for 24 h, the reaction mixture was concentrated by rotovap, and filtered through a short silica gel column by CH_2Cl_2 to afford a dark color solution. After concentration at low pressure, the residue was purified by column chromatography on silica gel (hexanes-CH_2Cl_2 1:1) to afford **145** as a yellow solid (6.68 g, 61%)

(±)-**145**: IR (cm^{-1}): 2474(m), 1911 (s), 1826 (s). ^1H NMR (400 MHz, $CDCl_3$): δ 8.53 (s, 1 H), 8.00 (s, 1H), 7.80 (s, 1H), 7.63 (s, 2H), 7.55 (s, 1H), 6.26 (s, 1H), 6.19 (s, 2H), 4.17 (d, J = 12.8 Hz, 1H), 4.01 (s, 1H), 3.99 (d, J = 12.8 Hz, 1H), 3.58 (d, J = 12.0 Hz, 1H),

3.50 (d, J = 12 Hz, 1H), 3.05 (s, 3H), 2.03 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 231.28, 231.25, 146.3, 144.3, 143.5, 136.2, 135.7, 134.4, 120.7, 105.6, 105.3, 105.1, 68.4, 67.8, 63.3, 63.2, 53.8, 20.7. HRMS (ESI) Calcd for $C_{18}H_{21}BMoN_6O_4$ ($[M]^+$): 494.0766. Found: 494.0779.



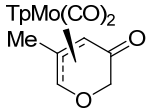
146

(±)-Dicarbonyl[hydridotris(1-pyrazolyl)borato][(2*S*,3*R*)-*η*-(3,4,5)-3-methoxyl-5-methyl-2*H*-pyran-3-yl]molybdenum, (±)-146.

In a Schlenk flask, Et_3N (0.87 g, 8.6 mmol, 10 equiv) was dissolved in dry, degassed CH_2Cl_2 (20 mL) at 0 ^oC under nitrogen. Then a solution of complex **148** (0.55 g, 0.86 mmol, 1 equiv) in CH_2Cl_2 was slowly added to the reaction. After being stirred at that temperature for 3 h, the solution was warmed to room temperature, filtered through a layer of Celite, and concentrated. Purification by column chromatography on silica gel (hexanes-ethyl acetate 4:1) afforded **146** as a yellow solid (71%).

(±)-**146**: IR (cm^{-1}): 2482(m), 1942 (s), 1849 (s). ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.11 (d, J = 2.0 Hz, 1H), 8.04 (d, J = 2.0 Hz, 1H), 7.98 (d, J = 2.0 Hz, 1H), 7.63 (d, J = 2.0 Hz, 1H), 7.62 (d, J = 2.0 Hz, 1H), 7.45 (d, J = 2.4 Hz, 1H), 7.37 (d, J = 2.8 Hz, 1H), 6.26 (t, J = 2.2 Hz, 1H), 6.22 (t, J = 1.8 Hz, 1H), 6.16 (t, J = 2.4 Hz, 1H), 5.63 (d, J = 1.2 Hz,1 H), 4.42 (t, J = 1.8 Hz, 1H), 3.55 (s, 3H), 1.13 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 226.7,

222.7, 149.9, 145.5, 142.4, 142.1, 136,4, 136.1, 134.3, 112.9, 107.9, 105.5, 105.3, 105.2, 61.4, 55.2, 52.8, 15.3. HRMS (ESI) Calcd for $C_{18}H_{20}BMoN_6O_4$ ($[M+H]^+$): 493.0688. Found: 493.0692.



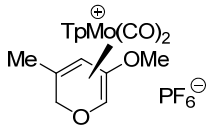
147

(±)-Dicarbonyl[hydridotris(1-pyrazolyl)borato][(2*S*)-η-(2,3,4)-3-methyl-5-oxo-5,6-dihydro-2*H*-pyran-2-yl]molybdenum, (±)-147.

Complex **146** (43.3 mg, 0.09 mmol, 1 equiv) was dissolved in a solution of HCl/EtOH/H_2O (1/8/1). Then the solution was stirred at room temperature for 2 h. After quenching the reaction with saturated $NaHCO_3$, the aqueous layer was extracted by CH_2Cl_2 (20 mL x 3). The organic layers were collected, and dried over $MgSO_4$. Purification by column chromatography on silica gel (hexanes-ethyl acetate 2:1) afforded **147** (0.38 g, 90%) as a yellow solid.

(±)-**147**: IR (cm^{-1}): 2490(m), 1965 (s), 1876 (s), 1652 (s). ^1H NMR (600 MHz, $CDCl_3$): δ 8.39 (d, *J* = 2.4 Hz, 1H), 7.94 (d, *J* = 1.8 Hz, 1H), 7.91 (s, 1H), 7.65 (d, *J* = 3.6 Hz, 1H), 7.63 (d, *J* =2.4 Hz, 1H), 7.47 (d, *J* = 2.4 Hz, 1H), 7.09 (d, *J* = 1.8 Hz, 1H), 6.29 (t, 1H), 6.26 (t, *J* = 1.8 Hz, 1H), 6.24 (t, *J* = 1.8 Hz, 1H), 4.6 (d, *J* = 1.8 Hz, 1H), 3.64 (d, *J* = 18.0 Hz,1H), 3.42 (d, *J* = 18.0 Hz, 1H), 1.44 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 223.6, 221.8, 194.7, 146.9, 143.4, 142.5, 137.0, 136.6, 134.6, 108.4, 106.1, 106.0, 105.7, 72.0, 68.5, 65.6, 16.2. HRMS (ESI) Calcd for $C_{17}H_{18}BMoN_6O_4$ ($[M+H]^+$): 479. 0531. Found:

479.0535.

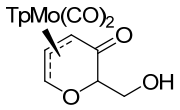


148

(±)-Dicarbonyl[hydridotris(1-pyrazolyl)borato][(2*S*,3*R*)-η-(2,3,4,5)-3-methoxyl-5-methyl-2*H*-pyran-3-yl]molybdenum hexaflourophosphate (±)-148.

In a Schlenk flask, complex **145** (0.4 g, 0.81 mmol, 1 equiv) was dissolved in dry, degassed CH_2Cl_2 (10 mL) at -78 ^oC under nitrogen. Then solid $TrPF_6$ (0.35 g, 0.89 mmol, 1.1 equiv) was added to the reaction. After being stirred at that temperature for 1 h, the solution was warmed to 0 ^oC and stirred for another 4.5 h at which time TBME was added to the reaction to form a brown precipitate. After removal of solvents, the precipitate was washed by TBME (2 x 50 mL), and dried by vacuum.

(±)-**148**: ^1H NMR (400 MHz, $CDCl_3$): δ 8.52 (d, *J* = 1.6 Hz, 1H), 8.05 (d, *J* = 2.0 Hz, 1H), 7.75 (d, *J* = 2.4 Hz, 1H), 7.71 (d, *J* = 2.0 Hz, 1H), 7.65 (d, *J* = 2.0 Hz, 1H), 7.49 (d, *J* = 2.4 Hz, 1H), 7.22 (d, *J* = 3.2 Hz, 1H), 6.47 (t, *J* = 2.4 Hz, 2H), 6.38 (t, *J* = 2.4 Hz, 1H), 6.21 (d, *J* = 2.8 Hz, 1H), 3.78 (d, *J* = 14 Hz,1 H), 3.38 (d, *J* = 14 Hz, 1H), 2.99 (s, 3H), 2.67 (s, 3H).



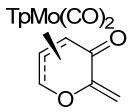
151

(±)-Dicarbonyl[hydridotris(1-pyrazolyl)borato][(2*S*,6*S*)-η-(2,3,4)-5-oxo-6-hydroxymethyl-5,6-dihydro-2*H*-pyran-2-yl]molybdenum, (±)-151.

In a Schlenk flask, complex **86** (1.0 g, 2 mmol, 1 equiv) was dissolved in dry, degassed CH_2Cl_2 (5 mL) at room temperature under nitrogen. Then Et_3N (0.36 mL, 2.4 mmol, 1.2 equiv) was added to reaction. After 5 min stirring, TBSOTf (0.52 ml, 2.1 mmol, 1.05 equiv) was added to reaction. The reaction was stirred at room temperature for another 30 min. After that, the reaction mixture was cooled to -78 ^oC. Then a premixed mixture (-78 ^oC) of $TiCl_4$ (3.20 ml, 3 mmol, 1.5 equiv) and trioxane (0.59 g, 6 mmol, 3 equiv) in dry CH_2Cl_2 (8 mL) was added to reaction. After stirring at -78 ^oC for 4 h, the reaction was slowly warmed to room temperature, and stirred overnight. After quenched the reaction with distilled water, the aqueous layer was extracted by CH_2Cl_2 (3 x 20 mL). The organic layers were collected, and dried over $MgSO_4$. Purification by column chromatography on silica gel (hexanes-ethyl acetate 1:2) afforded **151** as a yellow solid (50%).

(±)-**151**: IR (cm^{-1}): 3417 (br m), 1961 (s), 1872 (s). ^1H NMR (400 MHz, $CDCl_3$): δ 8.52 (d, *J* = 2.0 Hz, 1H), 7.91 (d, *J* = 2.0 Hz, 1H), 7.65 (d, *J* = 1.6 Hz, 1H), 7.62 (d, *J* = 2.4 Hz, 1H), 7.60 (d, *J* = 2.0 Hz, 1H), 7.52 (d, *J* = 2.4 Hz, 1H), 7.38 (dd, *J* = 4.8, 2 Hz,1H), 6.31 (t, *J* = 2.4 Hz, 1H), 6.26 (t, *J* = 2.2 Hz, 1H), 6.22 (t, *J* = 2.2 Hz, 1H), 4.81 (dd, *J* = 6.4, 2.4 Hz,1 H), 4.21 (dd, *J* = 6.4, 4.8 Hz, 1H), 3.89 (dd, *J* = 12.0, 4.0 Hz, 1H),

3.73 (dd, J = 12.0, 4.4 Hz, 1H), 3.43 (t, J = 4.8 Hz, 1H). ^{13}C NMR (150 MHz, $CDCl_3$): δ 224.6, 223.6, 194.4, 147.7, 144.0, 141.8, 136.6 (2C), 135.0, 107.6, 106.6, 106.3, 106.0, 76.9, 70.2, 65.2, 63.3. HRMS (ESI) Calcd for $C_{17}H_{18}BMoN_6O_5$ ($[M + H]^+$): 495.0480. Found: 495.0484.



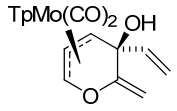
152

(±)-Dicarbonyl[hydridotris(1-pyrazolyl)borato][(2*S*)-η-(2,3,4)-5-oxo-6-methylene-5,6-dihydro-2*H*-pyran-2-yl]molybdenum, (±)-152.

To a solution of complex **151** (0.26 g, 0.53 mmol, 1 equiv) in dry, degassed CH_2Cl_2 (5 mL), DMAP (0.0968 g, 0.8 mmol, 1.5 equiv) and Et_3N (0.11 ml, 0.8 mmol, 1.5 equiv) were added at room temperature. After being stirred for 5min, MsCl (54 μl, 0.69 mmol, 1.3 equiv) was added to the reaction. The solution was stirred for 10 min. Then the reaction mixture was filtered through a short silica column by EtOAc. The solution was concentrated and dry, degassed CH_2Cl_2 (5 mL) was added under N_2. After the solution was cooled to 0 ^oC, DBU (0.12 mL, 0.8 mmol, 1.5 equiv) was added to the reaction. After being stirred at 0 ^oC for 10 min, the solution was filtered through a short silica column again by EtOAc. The solution was concentrated, and purified by column chromatography on silica gel (hexanes- ethyl acetate 2:1) to afford **152** as a yellow solid (88%).

(±)-**152**: IR (cm^{-1}): 2490 (w), 1965 (s), 1884 (s), 1660 (s). ^{1}H NMR (600 MHz,

$CDCl_3$): δ 8.52 (d, *J* = 1.8 Hz, 1H), 7.93 (d, *J* = 1.8 Hz, 1H), 7.65 (d, *J* = 1.8 Hz, 1H), 7.62 (d, *J* = 2.4 Hz, 1H), 7.60 (d, *J* = 2.4 Hz, 1H), 7.52 (d, *J* = 2.4 Hz, 1H), 7.17 (dd, *J* = 4.8, 2.4 Hz, 1H), 6.32 (t, *J* = 1.8 Hz, 1H), 6.27 (t, *J* = 1.8 Hz, 1H), 6.23 (t, *J* = 2.4 Hz, 1H), 5.46 (s, 1H), 4.96 (dd, *J* = 6.0, 2.4 Hz, 1 H), 4.67 (s, 1H), 4.38 (t, *J* = 6.0 Hz, 1H). ^{13}C NMR (150 MHz, $CDCl_3$): δ 224.4, 222.5, 196.7, 180.6, 150.2, 147.7, 144.0, 141.7, 136.7, 136.6, 135.0, 106.7, 106.4, 106.1, 103.7, 97.9, 72.3, 67.4. HRMS (ESI) Calcd for $C_{17}H_{16}BMoN_6O_4$ ($[M + H]^+$): 477.0375. Found: 477.0387.



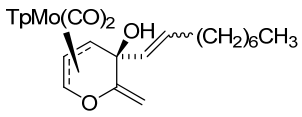
156

(±)-Dicarbonyl[hydridotris(1-pyrazolyl)borato][(2*S*,5*S*)-*η*-(2,3,4)-5-hydroxy-6-methylene-5-vinyl-5,6-dihydro-2*H*-pyran-2-yl]molybdenum, (±)-156.

In a flame dried Schlenk flask, complex **152** (30 mg, 0.063 mmol, 1 equiv) was dissolved in dry, degassed THF (1 mL) at -40 ^oC under nitrogen. Then vinyl magnesium bromide (1.0 M in THF, 0.3 mL, 0.3 mmol, 5 equiv) was added to reaction. After being stirred for 45 min, the reaction was cooled to -78 ^oC, and quenched with H_2O (0.5 mL). After warmed to room temperature, the reaction mixture was partitioned with brine and ethyl acetate. The organic layers were collected, and dried over $MgSO_4$. Purification by column chromatography on silica gel (hexanes-ethyl acetate 2:1) afforded **156** as a yellow solid (66%).

(±)-**156**: IR (cm^{-1}): 2486 (m), 1945 (s), 1853 (s), 1652 (s), 1505 (m). ^1H NMR (600

MHz, $CDCl_3$): δ 8.48 (d, *J* = 1.8 Hz, 1H), 7.94 (d, *J* = 2.4 Hz, 1H), 7.66 (d, *J* = 1.8 Hz,1H), 7.57 (d, *J* = 2.4 Hz, 1H), 7.56 (d, *J* = 2.4 Hz, 1H), 7.49 (d, *J* = 2.4 Hz, 1H), 6.96 (dd, *J* = 4.9, 3.0 Hz, 1H), 6.28 (t, *J* = 1.8 Hz, 1H), 6.22 (t, *J* = 1.8 Hz, 1H), 6.19 (t, *J* = 1.8 Hz, 1H), 6.12 (dd, *J* = 17.4, 10.8 Hz, 1H), 5.51 (d, *J* = 17.4 Hz, 1H), 5.11 (d, *J* = 10.2 Hz, 1H), 4.65 (s, 1H), 4.61 (dd, *J* = 7.8, 2.4 Hz, 1H), 3.66 (dd, *J* = 7.8, 4.8 Hz, 1H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 232.0, 224.4, 158.7, 146.8, 144.3, 142.8, 141.5, 136.2, 136.0, 134.5, 112.0, 106.1, 105.9, 105.7, 105.5, 92.6, 76.5, 76.1, 60.3. HRMS (ESI) Calcd for $C_{19}H_{20}BMoN_6O_4$ ([M+H$^+$]): 505.0688. Found: 505.0702.



155

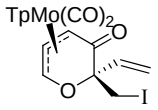
(±)-Dicarbonyl[hydridotris(1-pyrazolyl)borato][(2*S*,5*S*)-*η*-(2,3,4)-5-hydroxy-6-methylene-5-(non-1-enyl)-5,6-dihydro-2*H*-pyran-2-yl]molybdenum, (±)-155 (as a mixture of *Z* and *E* isomers).

In a flame dried Schlenk flask, complex **152** (50 mg, 0.1 mmol, 1 equiv) was dissolved in dry, degassed THF (2 mL) at -40 ^{o}C under nitrogen. Then a solution of **154** in THF (0.35 mL, 0.25 mmol, 4 equiv) was added to the reaction. After being stirred for 60 min, the reaction was cooled to -78 ^{o}C, and quenched with water. After warmed to room temperature, the reaction mixture was washed with brine and ethyl acetate. The organic layers were collected, and dried over $MgSO_4$. Purification by column chromatography on

silica gel (hexanes-ethyl acetate 2:1) afforded **155** as a yellow solid (54%).

*Since Z-**155** and E-**155** can not be separated by simple column chromatography on silica gel, the following ^1H NMR data of the mixture of Z and E isomers are only for reference.*

(±)-**155**: ^{1}H NMR (600 MHz, $CDCl_3$): δ 8.47 (d, *J* = 1.8 Hz, 1 H), 7.95 (d, *J* = 1.8 Hz), 7.93 (d, *J* = 1.8 Hz, 1H), 7.66 (s, 1H), 7.57 (m, 2 H), 7.49 (d, *J* = 2.4 Hz, 1H), 6.96 (m, 1H), 6.28(t, *J* = 2.4 Hz, 1H), 6.21 (t, *J* = 2.4 Hz, 1H), 6.19 (t, *J* = 1.8 Hz, 1H), 5.91 (dt, 0.3H), 5.75 (dd, 0.3H), 5.64 (d, *J* = 12.8 Hz, 1H), 5.38 (dt, *J* = 12.8 Hz, 9.6, 1H), 4.80 (dd, *J* = 10.8, 2.4 Hz, 1H), 4.68 (s, 1H), 4.63 (d, *J* = 2.4 Hz, 0.3H), 4.62 (s, 0.3H), 4.43 (s, 1.3H), 3.63 (dd, 0.3H), 3.59 (dd, *J* = 10.8, 7.2 Hz, 1H), 2.6-2.4 (m, 2H), 1.4-1.2 (m, 10H), 0.88 (m, 3H).



157

(±)-Dicarbonyl[hydridotris(1-pyrazolyl)borato][(2*S*,6*S*)-*η*-(2,3,4)-5-oxo-6-(iodomethyl)-6-vinyl-5,6-dihydro-2*H*-pyran-2-yl]molybdenum, (±)-157.

In a 10 mL Schlenk flask which was protected by aluminum foil, I_2 (18.4 mg, 0.07 mmol, 1.1 equiv) was added to a suspension of silver trifluoroacetate (17.5 mg, 0.08 mmol, 1.2 equiv) in dry CH_3CN (2 mL) under N_2 at room temperature. After being stirred for 30min, the reaction mixture was cooled to -40 ^oC. Then a solution of **156** (32.3 mg, 0.064 mmol, 1.0 equiv) in dry CH_3CN (2 mL) was slowly added to reaction. After

being stirred for 30 min, the reaction was quenched with $Na_2S_2O_3$. The reaction mixture was slowly warmed to room temperature, and washed with 0.1N $Na_2S_2O_3$ (3 x 20 mL). The combined organic layers were dried over $MgSO_4$. Purification by column chromatography on silica gel (hexanes- ethyl acetate) afforded **157** as a yellow solid (82%).

(±)-**157**: IR (cm^{-1}): 2490 (m), 1965 (s), 1880 (s), 1652 (s). ^1H NMR (600 MHz, $CDCl_3$): δ 8.54 (d, *J* = 1.2 Hz, 1H), 7.91 (d, *J* = 1.8 Hz, 1H), 7.68 (d, *J* = 2.4 Hz, 1H), 7.61 (d, *J* = 2.4 Hz, 1H), 7.59 (d, *J* = 2.4 Hz,1H), 7.56 (dd, *J* = 4.8, 2.4 Hz, 1H), 7.51 (d, *J* = 2.4 Hz, 1H), 6.32(t, *J* = 2.4 Hz, 1H), 6.26 (t, *J* = 2.4 Hz, 1H), 6.21 (t, *J* = 2.4 Hz, 1H), 5.58 (dd, *J* = 16.8, 10.2 Hz,1 H), 5.45(d, *J* = 18.8 Hz, 1H), 5.35 (d, *J* = 10.2 Hz, 1H), 4.74 (dd, *J* = 6.0, 2.4 Hz, 1H), 4.17 (t, *J* = 6.4 Hz, 1H), 3.65 (d, *J*=10.2 Hz, 1H), 3.10 (d, *J* = 11.4 Hz, 1H). HRMS (ESI) Calcd for $C_{19}H_{19}BIMoN_6O_4$ ($[M+H]^+$): 630.9654. Found: 630.9659.

X-Ray Crystallographic Study:

A suitable crystal of cationic diene **148** was coated with Paratone N oil, suspended in a small fiber loop and placed in a cooled nitrogen gas stream at 173 K on a Bruker D8 SMART APEX CCD sealed tube diffractometer with graphite monochromated MoK_α (0.71073Å) radiation. Data were measured using a series of combinations of phi and omega scans with 10 s frame exposures and 0.3^o frame widths. Data collection, indexing

and initial cell refinements were all carried out using SMART[129] software. Frame integration and final cell refinements were done using SAINT[130] software. The final cell parameters were determined from least-squares refinement on 5808 reflections. The SADABS[131] program was used to carry out absorption corrections.

The structure was solved using Direct methods and difference Fourier techniques (SHELXTL, V6.12).[132] Hydrogen atoms were placed their expected chemical positions using the HFIX command and were included in the final cycles of least squares with isotropic U_{ij} 's related to the atom's ridden upon. The C-H distances were fixed at 0.93 Å(aromatic and amide), 0.98 Å (methine), 0.97 Å (methylene), or 0.96 Å (methyl). All non-hydrogen atoms were refined anisotropically. Scattering factors and anomalous dispersion corrections are taken from the *International Tables for X-ray Crystallography*.[133] Structure solution, refinement, graphics and generation of publication materials were performed by using SHELXTL, V6.12 software. Additional details of data collection and structure refinement are given in Table 19.

[129] SMART Version 5.628, **2003**, Bruker AXS, Inc., Analytical X-ray Systems, 5465 East Cheryl Parkway, Madison WI 53711-5373.
[130] SAINT Version 6.36A, **2002**, Bruker AXS, Inc., Analytical X-ray Systems, 5465 East Cheryl Parkway, Madison WI 53711-5373.
[131] SADABS Version 2.10, **2003**, George Sheldrick, University of Göttingen,
[132] SHELXTL V6.12, **2002**, Bruker AXS, Inc., Analytical X-ray Systems, 5465 East Cheryl Parkway, Madison WI 53711-5373.
[133] A. J. C. Wilson (ed), *International Tables for X-ray Crystallography, Volume C.* Kynoch, Academic Publishers, Dordrecht, **1992**, Tables 6.1.1.4 (pp. 500-502) and 4.2.6.8 (pp. 219-222).

Table 19. Crystal data and structure refinement for complex 148

Identification code	**148**	
Empirical formula	C21 H26 B Cl6 F6 Mo N6 O4 P	
Formula weight	890.90	
Temperature	173(2) K	
Wavelength	0.71073 Å	
Crystal system	Monoclinic	
Space group	P2(1)/c	
Unit cell dimensions	a = 13.7762(15) Å	α= 90°.
	b = 12.5351(13) Å	β= 96.488(2)°.
	c = 19.665(2) Å	γ = 90°.
Volume	3374.1(6) $Å^3$	
Z	4	
Density (calculated)	1.754 Mg/m^3	
Absorption coefficient	0.984 mm^{-1}	
F(000)	1776	
Crystal size	0.40 x 0.35 x 0.15 mm^3	
Theta range for data collection	1.49 to 28.35°.	
Index ranges	-18<=h<=18, -16<=k<=16, -26<=l<=26	
Reflections collected	45507	
Independent reflections	8401 [R(int) = 0.0435]	
Completeness to theta = 28.35°	99.5 %	
Absorption correction	Semi-empirical from equivalents	
Max. and min. transmission	1.00 and 0.821634	
Refinement method	Full-matrix least-squares on F^2	
Data / restraints / parameters	8401 / 0 / 417	
Goodness-of-fit on F^2	1.088	
Final R indices [I>2sigma(I)]	R1 = 0.0582, wR2 = 0.1616	
R indices (all data)	R1 = 0.0714, wR2 = 0.1711	
Largest diff. peak and hole	2.089 and -1.158 $e.Å^{-3}$	

Table 20. Atomic coordinates (x 10^4) and equivalent isotropic displacement parameters ($Å^2$x 10^3) or 148. U(eq) is defined as one third of the trace of the orthogonalized U^{ij} tensor.

	x	y	z	U(eq)
Mo(1)	1151(1)	9953(1)	1998(1)	19(1)
B(1)	3019(3)	8271(4)	1908(2)	27(1)
C(1)	908(3)	11882(3)	1940(2)	29(1)
C(2)	1519(3)	11645(3)	2562(2)	27(1)
C(3)	1101(3)	10947(3)	3001(2)	25(1)
C(4)	100(3)	10680(3)	2804(2)	29(1)
C(5)	-539(3)	11523(4)	2431(2)	33(1)
C(6)	-440(4)	10039(4)	3292(2)	35(1)
C(7)	3132(4)	11583(5)	3141(2)	42(1)
C(8)	1814(3)	8616(3)	3449(2)	29(1)
C(9)	2494(4)	7858(4)	3700(2)	37(1)
C(10)	3025(3)	7638(4)	3173(2)	34(1)
C(11)	669(3)	8112(3)	854(2)	28(1)
C(12)	1109(4)	7242(4)	580(2)	34(1)
C(13)	2022(4)	7182(3)	926(2)	32(1)
C(14)	3065(3)	11060(4)	1430(2)	33(1)
C(15)	4009(4)	10797(4)	1302(3)	40(1)
C(16)	4124(3)	9745(4)	1501(3)	37(1)
C(17)	582(3)	10576(3)	1102(2)	28(1)
C(18)	-175(3)	9341(3)	1994(2)	27(1)
N(1)	1923(2)	8856(3)	2793(2)	23(1)
N(2)	2683(3)	8243(3)	2627(2)	26(1)
N(3)	1294(2)	8558(3)	1351(2)	24(1)
N(4)	2133(3)	7973(3)	1391(2)	25(1)
N(5)	2646(3)	10222(3)	1711(2)	26(1)
N(6)	3315(2)	9416(3)	1746(2)	26(1)
O(1)	-60(2)	12129(3)	1953(2)	35(1)
O(2)	2417(2)	12054(2)	2630(2)	31(1)
O(3)	246(3)	10866(3)	583(2)	45(1)

O(4)	-930(2)	8948(3)	1931(2)	38(1)
P(1)	1857(1)	3814(1)	65(1)	33(1)
F(1)	1588(3)	2938(3)	-513(2)	59(1)
F(2)	2563(3)	4378(3)	-413(2)	70(1)
F(3)	2118(3)	4690(3)	640(2)	58(1)
F(4)	1172(4)	3239(4)	536(2)	95(2)
F(5)	2752(3)	3107(3)	390(2)	77(1)
F(6)	994(3)	4532(4)	-275(2)	71(1)
C(1S)	2835(6)	668(6)	9555(4)	71(2)
C(2S)	5153(6)	3396(8)	10013(4)	80(2)
C(3S)	3482(5)	4073(5)	1966(4)	59(2)
Cl(1S)	3309(2)	317(2)	8801(1)	76(1)
Cl(2S)	2101(2)	-336(2)	9829(1)	87(1)
Cl(3S)	5255(2)	4066(2)	9256(1)	79(1)
Cl(4S)	5470(2)	2041(2)	9968(1)	84(1)
Cl(5S)	3508(2)	5411(1)	2168(1)	75(1)
Cl(6S)	4644(2)	3533(2)	1947(1)	86(1)

Table 21. Bond lengths [Å] and angles [°] for 148

Mo(1)-C(18)	1.980(4)	C(1)-C(2)	1.434(6)
Mo(1)-C(17)	2.004(4)	C(2)-O(2)	1.333(5)
Mo(1)-N(3)	2.184(3)	C(2)-C(3)	1.398(6)
Mo(1)-N(5)	2.223(4)	C(3)-C(4)	1.429(6)
Mo(1)-N(1)	2.255(3)	C(4)-C(5)	1.511(6)
Mo(1)-C(3)	2.342(4)	C(4)-C(6)	1.511(6)
Mo(1)-C(2)	2.420(4)	C(5)-O(1)	1.427(6)
Mo(1)-C(4)	2.441(4)	C(7)-O(2)	1.452(6)
Mo(1)-C(1)	2.443(4)	C(8)-N(1)	1.350(5)
B(1)-N(6)	1.535(6)	C(8)-C(9)	1.386(6)
B(1)-N(2)	1.537(6)	C(9)-C(10)	1.363(7)
B(1)-N(4)	1.544(6)	C(10)-N(2)	1.356(5)
C(1)-O(1)	1.371(6)	C(11)-N(3)	1.348(5)

C(11)-C(12)	1.385(6)	C(17)-Mo(1)-C(3)	119.13(16)
C(12)-C(13)	1.362(7)	N(3)-Mo(1)-C(3)	158.45(13)
C(13)-N(4)	1.346(5)	N(5)-Mo(1)-C(3)	104.45(14)
C(14)-N(5)	1.347(5)	N(1)-Mo(1)-C(3)	78.28(13)
C(14)-C(15)	1.393(7)	C(18)-Mo(1)-C(2)	119.09(16)
C(15)-C(16)	1.379(7)	C(17)-Mo(1)-C(2)	95.82(16)
C(16)-N(6)	1.327(6)	N(3)-Mo(1)-C(2)	160.11(14)
C(17)-O(3)	1.133(5)	N(5)-Mo(1)-C(2)	80.29(14)
C(18)-O(4)	1.146(5)	N(1)-Mo(1)-C(2)	99.12(13)
N(1)-N(2)	1.368(5)	C(3)-Mo(1)-C(2)	34.10(14)
N(3)-N(4)	1.364(5)	C(18)-Mo(1)-C(4)	62.13(16)
N(5)-N(6)	1.364(5)	C(17)-Mo(1)-C(4)	102.88(16)
P(1)-F(4)	1.571(4)	N(3)-Mo(1)-C(4)	140.93(14)
P(1)-F(6)	1.578(4)	N(5)-Mo(1)-C(4)	137.99(14)
P(1)-F(3)	1.588(3)	N(1)-Mo(1)-C(4)	92.60(13)
P(1)-F(2)	1.592(4)	C(3)-Mo(1)-C(4)	34.69(14)
P(1)-F(5)	1.592(4)	C(2)-Mo(1)-C(4)	58.93(14)
P(1)-F(1)	1.594(3)	C(18)-Mo(1)-C(1)	105.16(16)
C(1S)-Cl(2S)	1.737(7)	C(17)-Mo(1)-C(1)	62.28(15)
C(1S)-Cl(1S)	1.743(7)	N(3)-Mo(1)-C(1)	141.87(13)
C(2S)-Cl(3S)	1.730(8)	N(5)-Mo(1)-C(1)	87.93(14)
C(2S)-Cl(4S)	1.759(10)	N(1)-Mo(1)-C(1)	133.38(13)
C(3S)-Cl(5S)	1.723(6)	C(3)-Mo(1)-C(1)	59.66(14)
C(3S)-Cl(6S)	1.742(7)	C(2)-Mo(1)-C(1)	34.30(14)
		C(4)-Mo(1)-C(1)	64.66(14)
C(18)-Mo(1)-C(17)	83.02(18)	N(6)-B(1)-N(2)	109.1(3)
C(18)-Mo(1)-N(3)	80.32(15)	N(6)-B(1)-N(4)	107.4(3)
C(17)-Mo(1)-N(3)	81.54(15)	N(2)-B(1)-N(4)	107.6(3)
C(18)-Mo(1)-N(5)	159.88(15)	O(1)-C(1)-C(2)	120.6(4)
C(17)-Mo(1)-N(5)	89.97(16)	O(1)-C(1)-Mo(1)	110.5(3)
N(3)-Mo(1)-N(5)	80.00(13)	C(2)-C(1)-Mo(1)	72.0(2)
C(18)-Mo(1)-N(1)	97.44(15)	O(2)-C(2)-C(3)	128.4(4)
C(17)-Mo(1)-N(1)	162.53(15)	O(2)-C(2)-C(1)	117.0(4)
N(3)-Mo(1)-N(1)	81.33(12)	C(3)-C(2)-C(1)	114.4(4)
N(5)-Mo(1)-N(1)	83.71(12)	O(2)-C(2)-Mo(1)	121.9(3)
C(18)-Mo(1)-C(3)	95.41(16)	C(3)-C(2)-Mo(1)	69.9(2)

C(1)-C(2)-Mo(1)	73.7(2)	O(4)-C(18)-Mo(1)	173.4(4)
C(2)-C(3)-C(4)	115.5(4)	C(8)-N(1)-N(2)	105.8(3)
C(2)-C(3)-Mo(1)	76.0(2)	C(8)-N(1)-Mo(1)	134.7(3)
C(4)-C(3)-Mo(1)	76.4(2)	N(2)-N(1)-Mo(1)	119.4(2)
C(3)-C(4)-C(5)	117.3(4)	C(10)-N(2)-N(1)	109.5(3)
C(3)-C(4)-C(6)	118.8(4)	C(10)-N(2)-B(1)	128.9(4)
C(5)-C(4)-C(6)	112.2(4)	N(1)-N(2)-B(1)	121.6(3)
C(3)-C(4)-Mo(1)	68.9(2)	C(11)-N(3)-N(4)	106.6(3)
C(5)-C(4)-Mo(1)	107.6(3)	C(11)-N(3)-Mo(1)	131.4(3)
C(6)-C(4)-Mo(1)	125.8(3)	N(4)-N(3)-Mo(1)	121.9(2)
O(1)-C(5)-C(4)	113.8(4)	C(13)-N(4)-N(3)	109.1(3)
N(1)-C(8)-C(9)	110.5(4)	C(13)-N(4)-B(1)	130.3(4)
C(10)-C(9)-C(8)	105.5(4)	N(3)-N(4)-B(1)	120.6(3)
N(2)-C(10)-C(9)	108.6(4)	C(14)-N(5)-N(6)	106.3(4)
N(3)-C(11)-C(12)	109.7(4)	C(14)-N(5)-Mo(1)	132.4(3)
C(13)-C(12)-C(11)	105.7(4)	N(6)-N(5)-Mo(1)	121.0(3)
N(4)-C(13)-C(12)	109.0(4)	C(16)-N(6)-N(5)	109.9(4)
N(5)-C(14)-C(15)	109.9(4)	C(16)-N(6)-B(1)	128.3(4)
C(16)-C(15)-C(14)	104.7(4)	N(5)-N(6)-B(1)	120.6(3)
N(6)-C(16)-C(15)	109.1(4)	C(1)-O(1)-C(5)	114.5(3)
O(3)-C(17)-Mo(1)	175.7(4)	C(2)-O(2)-C(7)	117.6(4)
F(4)-P(1)-F(6)	92.2(3)	F(2)-P(1)-F(5)	89.3(3)
F(4)-P(1)-F(3)	90.0(2)	F(4)-P(1)-F(1)	89.9(2)
F(6)-P(1)-F(3)	90.4(2)	F(6)-P(1)-F(1)	89.3(2)
F(4)-P(1)-F(2)	179.0(3)	F(3)-P(1)-F(1)	179.6(2)
F(6)-P(1)-F(2)	88.7(3)	F(2)-P(1)-F(1)	89.6(2)
F(3)-P(1)-F(2)	90.5(2)	F(5)-P(1)-F(1)	90.6(2)
F(4)-P(1)-F(5)	89.8(3)	Cl(2S)-C(1S)-Cl(1S)	111.6(4)
F(6)-P(1)-F(5)	178.0(3)	Cl(3S)-C(2S)-Cl(4S)	112.4(4)
F(3)-P(1)-F(5)	89.8(2)	Cl(5S)-C(3S)-Cl(6S)	112.8(4)

Symmetry transformations used to generate equivalent atoms:

Table 22. Anisotropic displacement parameters ($Å^2$x 10^3) for 148. The anisotropic isplacement factor exponent takes the form: $-2\pi^2[h^2 a^{*2}U^{11} + ... + 2 h k a^* b^* U^{12}]$

	U^{11}	U^{22}	U^{33}	U^{23}	U^{13}	U^{12}
Mo(1)	23(1)	18(1)	16(1)	1(1)	2(1)	0(1)
B(1)	25(2)	27(2)	28(2)	1(2)	3(2)	2(2)
C(1)	39(2)	23(2)	23(2)	1(2)	3(2)	0(2)
C(2)	36(2)	22(2)	25(2)	-3(2)	6(2)	-1(2)
C(3)	31(2)	25(2)	20(2)	-4(1)	5(2)	0(2)
C(4)	33(2)	27(2)	28(2)	-3(2)	9(2)	3(2)
C(5)	34(2)	30(2)	37(2)	-4(2)	9(2)	7(2)
C(6)	35(2)	41(3)	31(2)	-3(2)	13(2)	-2(2)
C(7)	40(3)	55(3)	30(2)	1(2)	-1(2)	-11(2)
C(8)	35(2)	29(2)	23(2)	4(2)	3(2)	-4(2)
C(9)	46(3)	38(2)	26(2)	12(2)	-8(2)	-1(2)
C(10)	34(2)	31(2)	33(2)	9(2)	-7(2)	2(2)
C(11)	36(2)	26(2)	21(2)	-2(2)	1(2)	-4(2)
C(12)	50(3)	29(2)	24(2)	-7(2)	6(2)	-5(2)
C(13)	44(3)	25(2)	29(2)	-4(2)	11(2)	3(2)
C(14)	40(2)	32(2)	28(2)	-1(2)	12(2)	-10(2)
C(15)	43(3)	42(3)	39(2)	-4(2)	20(2)	-16(2)
C(16)	29(2)	45(3)	37(2)	-5(2)	10(2)	-3(2)
C(17)	35(2)	24(2)	23(2)	0(2)	1(2)	3(2)
C(18)	26(2)	31(2)	24(2)	-2(2)	5(2)	3(2)
N(1)	27(2)	22(2)	20(2)	2(1)	1(1)	1(1)
N(2)	27(2)	26(2)	26(2)	5(1)	-1(1)	2(1)
N(3)	28(2)	22(2)	20(2)	-1(1)	2(1)	0(1)
N(4)	29(2)	23(2)	24(2)	-1(1)	7(1)	1(1)
N(5)	32(2)	24(2)	23(2)	0(1)	6(1)	0(1)
N(6)	22(2)	30(2)	26(2)	-2(1)	3(1)	-1(1)
O(1)	40(2)	26(2)	37(2)	3(1)	5(1)	10(1)
O(2)	38(2)	29(2)	27(2)	-4(1)	6(1)	-8(1)
O(3)	64(2)	39(2)	27(2)	7(1)	-14(2)	4(2)
O(4)	27(2)	43(2)	43(2)	-4(2)	7(1)	-6(1)

P(1)	46(1)	30(1)	22(1)	2(1)	3(1)	4(1)
F(1)	85(3)	46(2)	42(2)	-14(1)	-5(2)	-6(2)
F(2)	83(3)	74(3)	58(2)	-2(2)	30(2)	-19(2)
F(3)	81(3)	47(2)	42(2)	-16(2)	-8(2)	10(2)
F(4)	138(4)	91(3)	64(3)	8(2)	52(3)	-38(3)
F(5)	95(3)	55(2)	71(3)	-8(2)	-33(2)	29(2)
F(6)	62(2)	72(3)	75(3)	0(2)	-15(2)	25(2)
C(1S)	99(6)	57(4)	63(4)	-16(3)	40(4)	-19(4)
C(2S)	84(5)	104(7)	54(4)	1(4)	22(4)	14(5)
C(3S)	60(4)	44(3)	67(4)	-1(3)	-15(3)	-2(3)
Cl(1S)	73(1)	97(1)	62(1)	3(1)	28(1)	-3(1)
Cl(2S)	101(2)	83(1)	90(1)	-26(1)	61(1)	-39(1)
Cl(3S)	82(1)	97(2)	60(1)	4(1)	18(1)	-12(1)
Cl(4S)	97(2)	79(1)	79(1)	-10(1)	25(1)	-11(1)
Cl(5S)	120(2)	45(1)	58(1)	-1(1)	8(1)	10(1)
Cl(6S)	75(1)	72(1)	102(2)	-23(1)	-24(1)	24(1)

Table 23. Hydrogen coordinates (x 10^4) and isotropic displacement parameters (Å^{2}x 10^3) for 148

	x	y	z	U(eq)
H(1)	3573	7766	1875	32
H(1)	1239	12258	1582	34
H(3)	1455	10717	3449	30
H(5A)	-1120	11173	2185	40
H(5B)	-770	12016	2772	40
H(6A)	-1108	9901	3082	53
H(6B)	-461	10441	3718	53
H(6C)	-103	9360	3392	53
H(7A)	2915	11670	3595	63
H(7B)	3763	11940	3130	63
H(7C)	3202	10822	3043	63
H(8)	1337	8923	3702	35
H(9)	2573	7556	4146	45

H(10)	3549	7142	3187	40
H(11)	26	8357	713	34
H(12)	832	6784	226	41
H(13)	2502	6665	850	39
H(14)	2760	11731	1333	39
H(15)	4473	11243	1118	48
H(16)	4690	9324	1469	44
H(1S1)	3379	813	9917	85
H(1S2)	2446	1330	9479	85
H(2S1)	4472	3453	10125	96
H(2S2)	5584	3740	10387	96
H(3S1)	3102	3973	1512	70
H(3S2)	3144	3681	2307	70