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Allylic C-H Functionalization of Disubstituted Olefins via Rhodium-π-Allyl Intermediates and Development of a Chiral Cyclopentadienyl Catalyst

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Abstract

Allylic C-H Functionalization of Disubstituted Olefins via Rhodium-π-Allyl Intermediates and Development of a Chiral Cyclopentadienyl Catalyst

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Allylic C-H functionalization has been an emerging field over the last decade due to the ability to convert inert C-H bonds into C-N, C-O, and C-C bonds. In the past two years the Blakey group has developed methodology for rhodium (III) catalyzed intermolecular allylic C-H amination and etherification of 1,2-disubstituted olefins. The allylic amination methodology was found to be regioselective however was not enantioselective. Therefore it was proposed that methodology for allylic C-H alkylation of 1,2-disubstiuted olefins could be developed. Optimization for this method was done using diphenylpropene as the substrate and dimethylmalonate as the nucleophile. This methodology was found to tolerate five nucleophiles with moderate to high yields. The nucleophiles that tolerated this system contained one nitro, ketone, ester, or two esters. The regioselectivity of the system was investigated using β-alkyl-styrene derivatives and a variety of the best nucleophiles from the reaction scope with diphenylpropene. However, these reactions were found to be unsuccessful. Mechanistic studies were performed using dimethyl malonate and diphenylallyl acetate to determine if this method goes through the same mechanism as allylic amination. It was determined that product was made with only having either the rhodium or silver catalyze the reaction. This result is similar to mechanistic studies done for allylic amination and it was determined that allylic alkylation goes through the same mechanism as the allylic amination. Another goal was to develop a chiral sulfoxide cyclopentadienyl rhodium catalyst to be able to develop a new method for allylic amination that would be enantioselective. Conditions for 2,3,4,5-tertamethylcyclopenta-1,5-dien-1-yl)naphthalene ligand were first attempted to be developed through a naphthalene Grignard reaction. It was determined that by either a one-pot or two-step synthesis neither obtained the desired product. Therefore a naphthalene turbo-Grignard was then investigate and was found that desired product was made however the purification of this process is still being investigated.

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Introduction

C-H functionalization has been a growing field over the last decade due to the ability to convert historically inert C-H bonds to C-N, C-O, and C-C.[1-11] These methods are important to investigate because C-H functionalization can lead to more efficient syntheses of drugs and natural products.[4-5] Allylic substitution reactions have been used in synthesis since their discovery in the late 1960s by Tsuji and Trost.[4] In order for Tsuji-Trost type allylic substitution reactions to proceed, a low-valent transition metal catalyst usually Pd^0 must first coordinate to the olefin and oxidatively insert into the π-system, expelling the leaving group to form the π-allyl intermediate that can interact with an array of different nucleophiles to generate new allylic compounds.[4] Later it was found that alkynes, allenes, and conjugated dienes could be used as pre-oxidized alternatives to allylic leaving groups for entry into π-allyl intermediates (Figure 1).[4-5] The one downfall to this chemistry is that these pre-oxidized substrates need to be prepared before running these reactions. Therefore, scientists then started to investigate allylic C-H functionalization reactions in order to directly functionalize unactivated olefins.

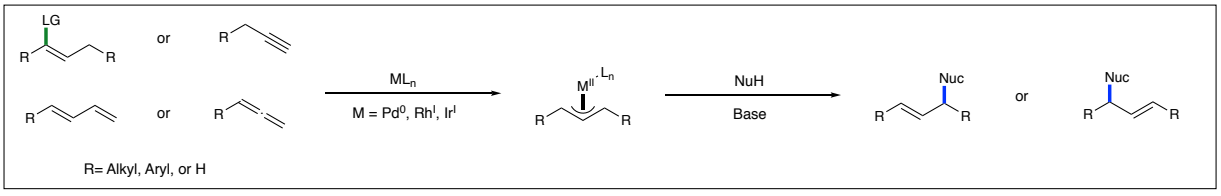


Figure 1. Historical allylic functionalization via a metal π-allyl intermediate

The White group was able to develop a method for C-H functionalization of terminal olefins through π-allyl intermediates using palladium(II)-sulfoxide precatalysts and either benzoquinone or DMBQ/AcOH as an oxidant (Figure 2).[6-8] However, this method was limited to

malonate type nucleophiles, electron deficient amine nucleophiles, and acetates to obtain C-C, C-N, and C-O bonds on only terminal olefins.

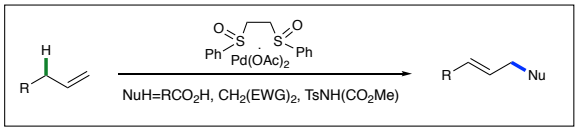


Figure 2: Palladium catalyzed allylic C-H alkylation of terminal olefins

Several years later Cossy demonstrated unprecedented reactivity with $RhCp^*$ to catalyze intramolecular allylic C-H amination through a rhodium π-allyl intermediate (Figure 3).[9] Unlike the White's group methodology these reaction conditions were able to tolerate both terminal and internal olefins. This reaction also tolerates alkyl amines with a single electron-withdrawing group, which is distinct from White group's literature. However, these reaction conditions were limited to intramolecular allylic C-H amination.

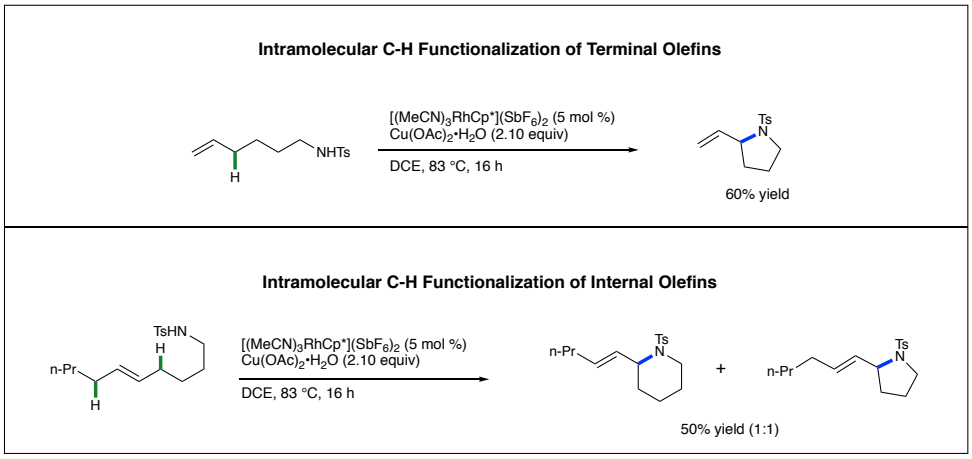


Figure 3: Rhodium catalyzed allylic C-H alkylation of intramolecular disubstituted olefins

Later Tanaka isolated π-allyl intermediates via C-H functionalization from terminal and disubstituted olefins using $[Cp^ERhCl_2]_2$.[10] The proposed intermediate from Cossy was isolated and subjected to the reaction conditions developed by Cossy to generate the amination

product (Figure 4), which supported that these reactions proceeded through a π-allyl intermediate. The isolated rhodium π -allyl complexes formed from *trans*-2-octene showed selectivity for the internal regioisomer. This result suggests that a Rh(III)Cp* derivative may be able to catalyze intermolecular allylic C-H functionalization reactions with disubstituted olefins.

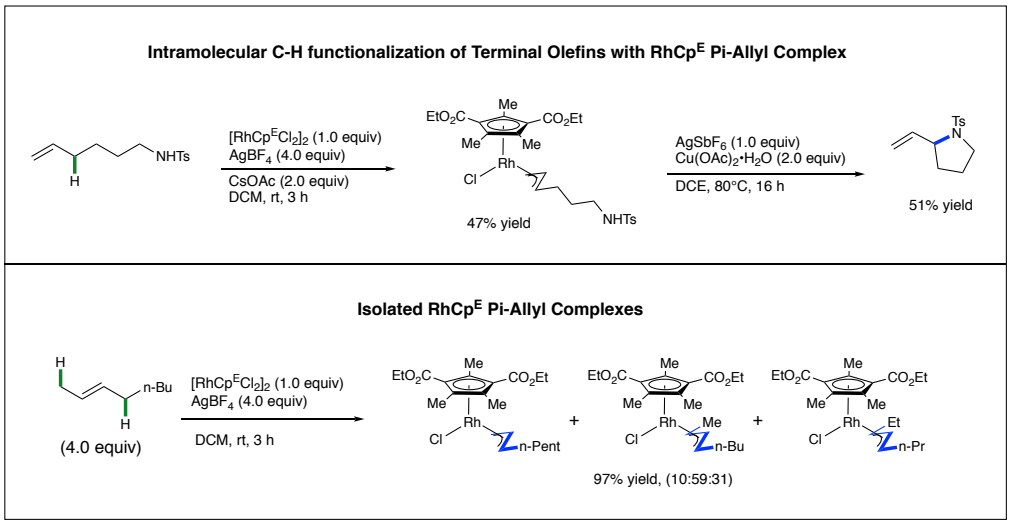


Figure 4: Isolated rhodium π-allyl complexes and their reactivity

Since then the Blakey group has developed a methodology for a rhodium (III) catalyzed intermolecular allylic C-H amination and etherification of 1,2-disubstituted olefins (Figure 5).[11-12] The amination reaction was able to tolerate a variety or aryl alkenes including electron withdrawing and electron donating aryl ring groups with good regioselectivities. This reaction also tolerated a wide variety of singly protected; substituted amine nucleophiles.[11] The etherification reaction was able to tolerate a wide variety of nucleophiles including electron poor and electron rich alcohols. This methodology was also able to tolerate alcohols with more complex functionality that can be of relevance for medicinal chemistry. The reaction also tolerates a range of aryl-alkyl disubstituted olefin substrates and terminal olefins.[12] These

methodologies developed in our lab and supporting literature suggests that a Rhodium (III) catalyzed allylic C-H alkylation of 1,2-disubstituted olefins system can be established.

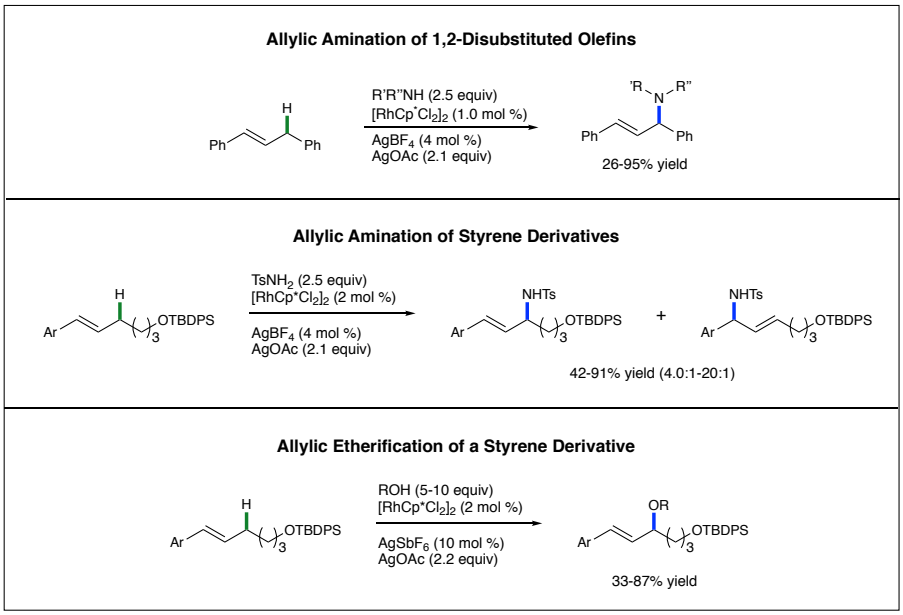


Figure 5: Allylic C-H functionalization methodologies developed in the Blakey group

Additionally the allylic C-H amination methodology developed in the Blakey group resulted in a high regioselectvity for the conjugated amine however, this reaction was not enantioselective.[11] Therefore it was thought if a chiral RhCp* catalyst could be used to make an enantioselective allylic C-H amination reaction. The field of chiral catalyst development has continued to be of importance today in order to develop methodologies to obtain enantio- and regioselective reactions that have the potential to be important in industry processes.[13] Trost developed a chiral sulfoxide-ligated cyclopentadienyl ruthenium complex that was synthesized in six linear steps.[14] The enantio- and regioselectiviy of the complex in catalytic reactions was investigated with cinnamyl chloride as the substrate with a range of nucleophiles including phenols, carboxylic acids and water. It was found that this complex was able to yield branched-

selective asymmetric allylic alkylation of phenols and carboxylic acids (Figure 6).[14] Even though this ligand achieved high enantio- and regioselectivity it was limited to be used with phenols and carboxylic acids.

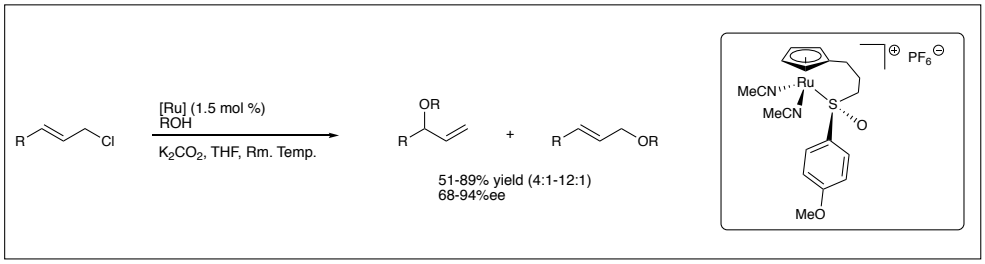


Figure 6: Enantio- and regioselective allylic substitution

A few years later Trost developed a chiral indenylruthenium complex to perform a C-H insertion reaction with a 90:10 er (Figure 7).[15]

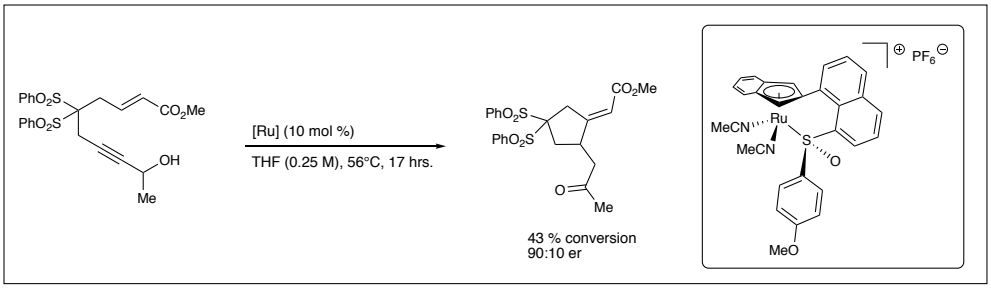


Figure 7: Enantioselective C-H insertion reaction

We proposed that a chiral sulfoxide cyclopentadienyl rhodium complex can be developed and used to catalyze enantio- and regioselective allylic C-H amination reactions. The sulfoxide group of the ligand will remain unchanged when compared to the Trost chiral indenylruthenium complex however; the ligand will contain a cyclopentadienyl instead of an indenyl group like the chiral sulfoxide-ligated cyclopentadienyl ruthenium complex (Figure 8).

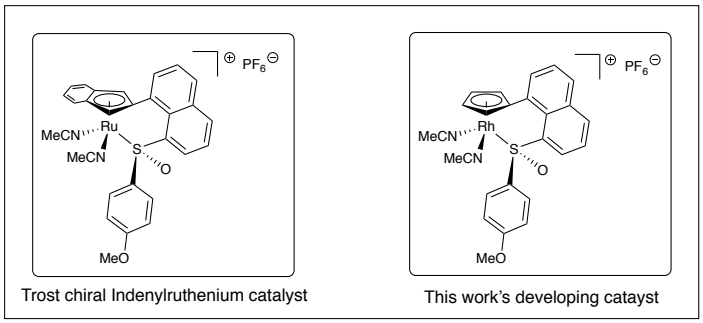


Figure 8: Trost indenylruthenium complex versus the catalyst being developed for this project

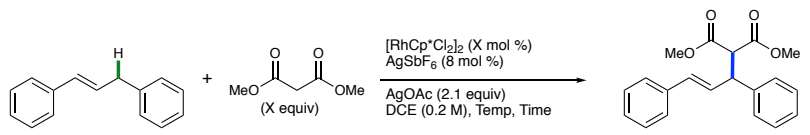
This project's focus is in the development of a chiral sulfoxide cyclopentadienyl ligand to catalyze enantioselective allylic C-H amination reactions while yielding similar regioselectivity to what has been previously discovered in the group. When the sulfoxide cyclopentadienyl ligand is synthesized it will be complexed onto rhodium to develop the catalyst. The catalyst activity will be measured against the original allylic C-H amination conditions to determine if it yields better enantio- and regioselectivity. If the catalyst produces higher enantio- and regioselectivity then the original allylic C-H amination conditions then this methodology will be valuable for synthesizing complex molecules.

Results and Discussion

Allylic C-H Alkylation

The model system that was chosen was 1,3-diphenyl propene with dimethyl malonate due to the symmetrical π-allyl intermediate that would form. Based off of conditions previously developed in the Blakey group in allylic amination $[RhCp^*Cl_2]_2$ catalyst, $AgSbF_6$ as the halide scavenger, AgOAc as the oxidant, and DCE were used for this reaction. Optimization studies were done to determine optimal conditions for this methodology by investigating the mole percent of $[RhCp^*Cl_2]_2$, equivalence of dimethylmalonate, time, and temperature (Table 1). No

product was observed after a 6 hour reaction time at 40°C (Entry 1). The reaction was run at 40°C for 24 hours with no product observed (Entry 2). The reaction was run at 60°C and there was no observable product after 6 hours (Entry 3). When the reaction was run for 24 hours at 60°C the product was observed in good yield of 73% (Entry 4). The reaction temperature was increased to 80°C and product was observed after 6 and 24 hours with yields of 62% and 78%, respectively (Entries 5-6). By increasing the reaction temperature from 60°C to 80°C over 24 hours the yield in product increased by 5% (Entry 4 vs. Entry 6).



Entry	Temp (°C)	Time (h)	[Rh] (mol %)	Nuc. (equiv)	% Yield[a]
1	40	6	2.0	2.5	0
2	40	24	2.0	2.5	0
3	60	6	2.0	2.5	0
4	60	24	2.0	2.5	73
5	80	6	2.0	2.5	62
6	**80**	**24**	**2.0**	**2.5**	**78**
7	80	24	1.0	2.5	44
8	80	24	2.5	2.5	75
9	80	24	5.0	2.5	0
10	80	24	2.5	1.25	76
11	80	24	2.5	5.0	99

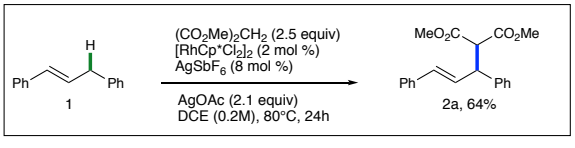
[a] Yields were determined by ^{1}H NMR using 1,4-dinitrobenzene as an internal standard.

Table 1: Optimization of dimethyl malonate with diphenylpropene

After determination of the optimal temperature of 80°C and time of 24 hours investigations of the optimal mole percent of rhodium catalyst were investigated. 1 mol % of the rhodium catalyst was used instead of the 2.0 mol % used for the previous trials and obtained a product yield of 44% (Entry 7). Decreasing by 1 mol % of rhodium lead to a decrease of 34% yield of product (Entry 7 vs. Entry 6). This led to the conclusion that at least 2 mol % of

the rhodium catalyst is needed for this reaction. 2.5 mol % of the rhodium catalyst was used (Entry 8) and lead to a 3% decrease in product formation (Entry 8 vs. Entry 6). However, due to errors in determination of the product yield by ^{1}H NMR these results are statistically equivalent. In order to determine if the higher mol % of rhodium catalyst was leading to a decrease in the formation of product 5.0 mol % of rhodium catalyst was used (Entry 9). This reaction was completely shut down by the 5.0 mol % of rhodium catalyst and lead to no formation of product. Therefore, it was determined that 2.0 mol % of $[RhCp^{*}Cl_2]_2$ was the optimal amount for this reaction.

Next the equivalence of the nucleophile was investigated. 1.25 equivalents of the nucleophile was used (Entry 10) instead of 2.5 equivalents that was used in all of the previous entries and obtained a yield of 76% which was observed to have a slight decrease in formation of product compared to the optimal conditions determined so far (Entry 10 vs. Entry 6). Therefore, the equivalence of nucleophile was increased to above 2.5 to hopefully obtain a higher yield of product. 5.0 equivalents of the dimethylmalonate was used and produced the highest yield of product of 99% (Entry 11). However, it was determined that the yield in Entry 6 with lower catalyst loading was sufficient for industrial methods and had less remaining nucleophile which caused problems in purification of the product. It was found that under these optimized conditions that product 2a was isolated in 64% yield (Scheme 1).



Scheme 1: Conditions used for allylic C-H alkylation of disubstituted olefins

Having identified the effective reaction conditions for allylic alkylation of a disubstituted olefin, the reaction was probed with various malonate type nucleophiles to discover the reactivity of the system developed (Table 2).

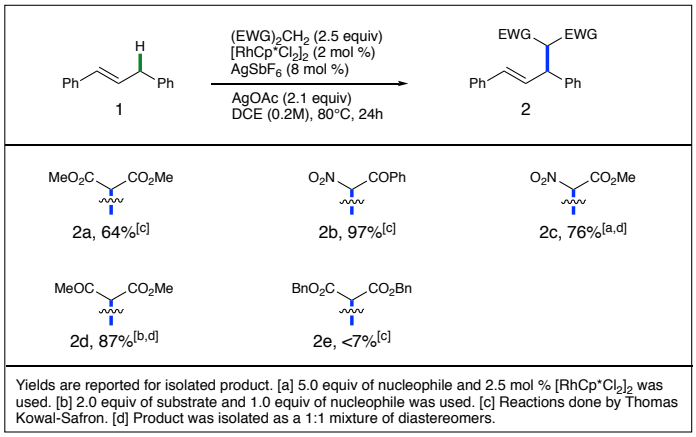


Table 2: Reaction scope with respect to the carbon nucleophiles for allylic alkylation

The scope contains a total of five examples with product yields from <7% to 97%. The scope shows that malonate type nucleophiles with ester, ketone, and nitro groups work effectively for alkylation. It was observed that product 2b had the highest yield of 97% out of all the nucleophiles studied with a nitro and ketone group on either side. Product 2c with a nitro and ester group had a yield of 76%, which was lower than product 2b. This result can be explained by the difference in effects of the ketone versus the ester. The ketone is more electron withdrawing then the ester and therefore will allow for the C-H on the central carbon to be deprotonated easier to then obtain the anion and generate the active nucleophile. Product 2d has a ketone and an ester and has a yield of 87% which is lower yield than 2b with a yield of 97%. This result is most likely observed since the nitro group is more electron withdrawing than an ester group due to the electronegative nitrogen element instead of a carbon and therefore will allow for the C-H on the central carbon to be deprotonated easier to

generate the active nucleophile. Comparing the results between 2d with an 87% yield to 2c with a lower yield of 76% is described by the effect of the ketone versus nitro group. The ketone is more electron withdrawing then the nitro and therefore allows the C-H on the central carbon to be deprotonated easier to develop the active nucleophile. This leads to a higher yield of product 2d then 2c, which were both, isolated in a 1:1 mixture of diastereomers. Product 2e had two benzyl esters and obtained the lowest yield of less than 7% which is most likely do to the fact that the methyl esters in 2a are more electron withdrawing then the benzyl esters leading to an easier deprotonating on the central carbon to generate the active nucleophile. Therefore, this system with diphenylpropene used as a symmetrical substrate was determined to work most effectively with one nitro, ketone, or ester group on the nucleophile and two ester groups were compatible with the system.

There were also many nucleophiles that were not tolerated in this system (Table 3).

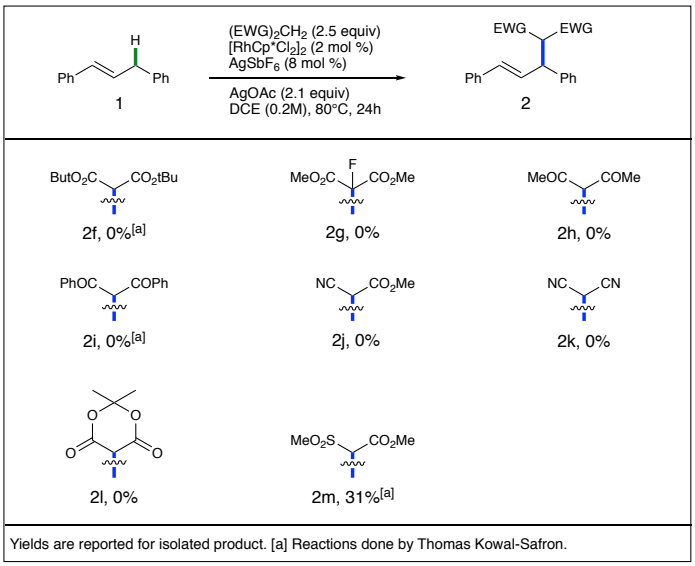


Table 3: Reaction scope of incompatible carbon nucleophiles for allylic alkylation

There was no product observed with 2f even when inverting the stoichiometry of substrate versus nucleophile it was concluded that this nucleophile was too bulky and due to steric hindrance this product did not form. In 2g the same nucleophile as 2a was used expect the center carbon now had a fluorine group instead of two hydrogens. Since fluorine and hydrogen are similar sizes to one another it was determined that this would be a good reaction to try and by having a nucleophile containing fluorine in the reaction scope it would show greater utility of the method developed. However, the fluorine was found to inhibit the reactivity with no observed product. It was also found that methyl- or phenyl-substituted 1,3-diketones whether they were both with methyl or phenyl groups as shown in 2h and 2i did show the appearance of product in the baseline at 24hrs and 48hrs but the desired product was too small to isolate. The thought is that there is a side reaction going on that is not allowing for more product to be created even after a longer reaction time. No product was observed in 2j and 2k, which both contained nitrile groups. This result is more likely observed since it is known that nitriles can coordinate to rhodium and stop the reaction. The ring six membered ring nucleophile with two esters did not produce product 2l probably because this nucleophile is unstable under acetic conditions and will therefore decompose. The last nucleophile tried was an ester with a sulfone group, which did not produce product 2m due to the sulfone inhibiting reactivity. Overall, the system was not able to tolerate nitriles, tert butyl groups, fluorine, sulfone, and two ketone groups on both sides of the nucleophile.

Next the regioselectivity of the system was probed by using an unsymmetrical substrate. The substrates were β-alkyl-styrene derivatives used to investigate the regioselectivity, one with a phenyl group and another with a 4-methoxyphenyl group (Tables 4-5). The nucleophiles that were used with this substrate were dimethylmalonate, methyl nitroacetate, and methyl acetoacetate. These nucleophiles were chosen because dimethylmalonate was used for the model system and the other two are a variety of nucleophiles that gave the highest yield of product with diphenylpropene.

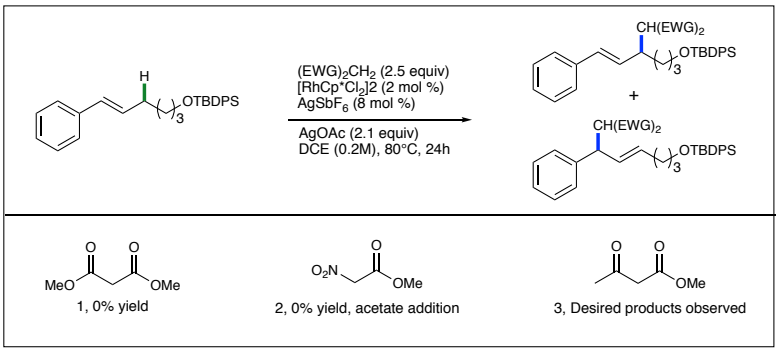


Table 4: Reaction scope with phenyl β-alkyl-styrene derivative and various malonate type nucleophiles

It was observed that with dimethylmalonate as the nucleophile there was no desired products formed and no starting material was present for both of the β-alkyl-styrene derivatives used (Table 4 and 5, Entry 1). Even when inverting equivalents of substrate to nucleophile there was still no desired products formed.

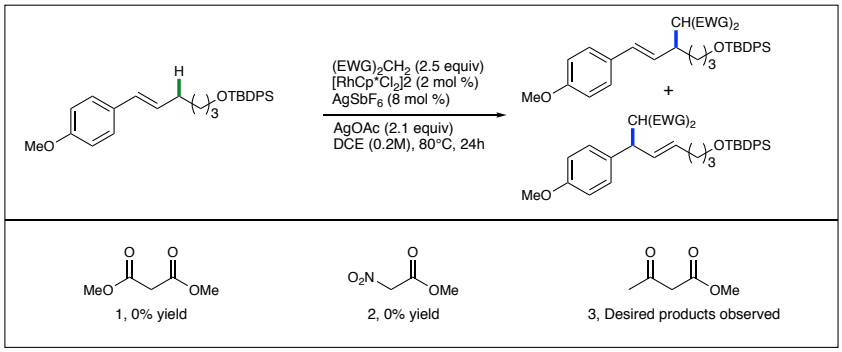


Table 5: Reaction scope with 4-methoxyphenyl β-alkyl-styrene derivative and various malonate type nucelophiles

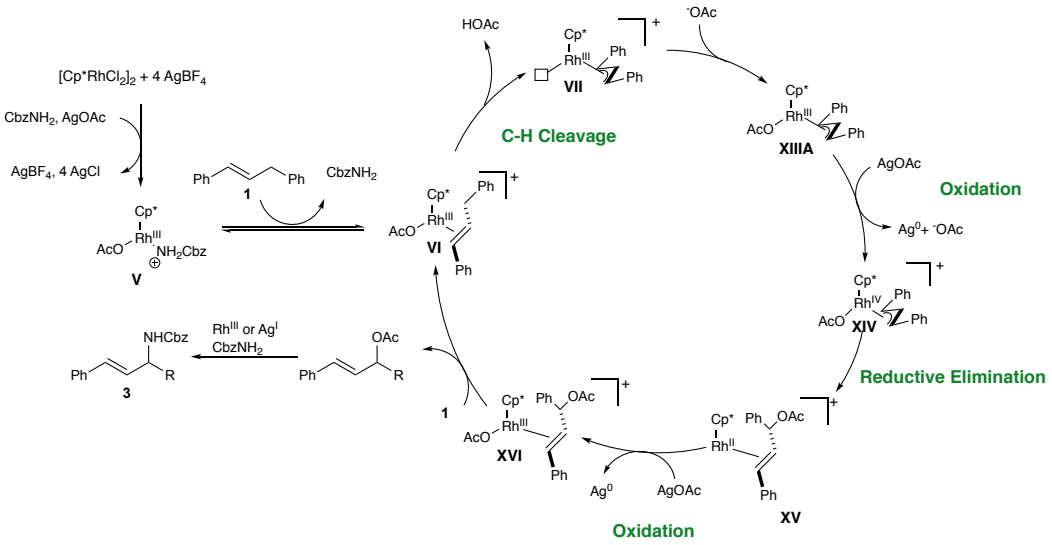
Next methyl nitroacetate was used with the phenyl β-alkyl-styrene and acetate addition was observed when the reaction was run at 40°C, 60°C, and 80°C (Table 4, Entry 2). Different temperatures were investigated since it was thought that maybe at 80°C the starting material was getting degraded, as no starting material was present in the previous reactions with dimethylmalonate. Acetate addition is known to form first before the S_N1 reaction happens to form the allylic amine according to the mechanism for allylic C-H amination. Therefore, no matter what temperature this reaction is run at it is not able to continue on after the acetate addition. This is probably due to the fact that the phenyl β-alkyl-styrene derivative is not able to form as stable of an allyl cation as the diphenylpropene does to be able to do the S_N1 reaction. When methyl nitroacetate was used as the nucleophile with 4-methoxyphenyl β-alkyl-styrene there were olefin peaks in the crude ^{1}H NMR suggesting that the desired product had possibly been made (Table 5, Entry 2). A new spot was observed by TLC and after attempted purification other small peaks started to appear in the ^{1}H NMR that were not originally in the crude ^{1}H NMR. The product with some impurities was left on the high vacuum over night. The ^{1}H NMR was taken the next morning and it was observed that the product degraded and it was

determined that the product was not stable and no yield could be determined. It should be noted that this reaction was redone multiple times and all the same observations were made.

When the reaction was run with methyl acetoacetate and both of the β-alkyl-styrene derivatives there were desired products formed however purification of these products was not possible (Table 4 and 5, Entry 3). These results can be explained by the fact that unlike the diphenylpropene substrate the styrene allyl-cation is not as stable and persistent and these malonate type nucleophiles are not the best nucleophiles due their ability to stabilized electron density. Therefore it was determined that no other nucleophiles or different β-alkyl-styrene derivatives would be tried at this time since it was very hard in getting these reactions to work with even trying the best nucleophiles.

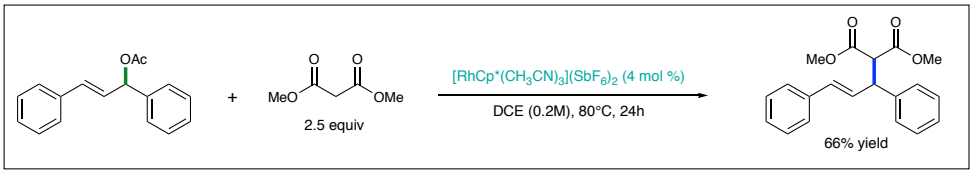
The mechanism for allylic C-H amination with diphenylpropene has been investigated and determined in the Blakey group (Scheme 2). The mechanism for allylic C-H amination starts by $AgBF_4$ abstracting chlorides from the rhodium dimer to form a dicationic Cp^*Rh^{2+} which is then intercepted by an acetate ligand and benzyl carbamate to form rhodium complex V. This complex then undergoes an associative ligand exchange to replace the benzyl carbamate ligand with diphenylpropene to obtain rhodium complex VI. This complex VI then undergoes concerted metallation deprotonation which is the rate determining step to yield the cationic Rh(π-allyl) complex VII. Complex VII then gets intercepted by an acetate ion to yield the new complex XIIIA. This complex then goes through a single electron oxidation to bring the rhodium (III) complex to a rhodium (IV) complex XIV which then reductively eliminates the allylic acetate to obtain a rhodium (II) complex XV. The XV complex then goes through another single electron

oxidation and a ligand exchange to release allylic acetate to get back to the rhodium complex VI. Meanwhile the allylic acetate gets converted into the allylic amine product through an off cycle Lewis acid catalyzed substitution which can either be S_N1 or S_N2. However, by the mechanism it is more likely to favor S_N1 due to the formation of a highly stabilized benzyl allyl cation. Therefore, it was thought that the allylic C-H alkylation with diphenylpropene went through the same mechanism.



Scheme 2: Proposed mechanism for rhodium catalyzed allylic C-H amination

In order to determine if this was true some mechanistic studies were done to determine the mechanism for this system. These mechanistic studies were done with diphenylallyl acetate and dimethylmalonate. The first mechanistic reaction was using Rhodium Cp^* monomer and the desired product was made and isolated in 66% yield (Scheme 3). This determined that this reaction was able to proceed with just the rhodium catalyst being added to the reaction with the nucleophile and having acetate already on the substrate.



Scheme 3: Mechanistic study for allylic C-H alkylation with Rhodium Cp* monomer

The mechanistic reaction with silver hexafluoroantimonate added to the reaction with the diphenylallyl acetate and dimethylmalonate obtained the product in an isolated yield of 44% (Scheme 4).

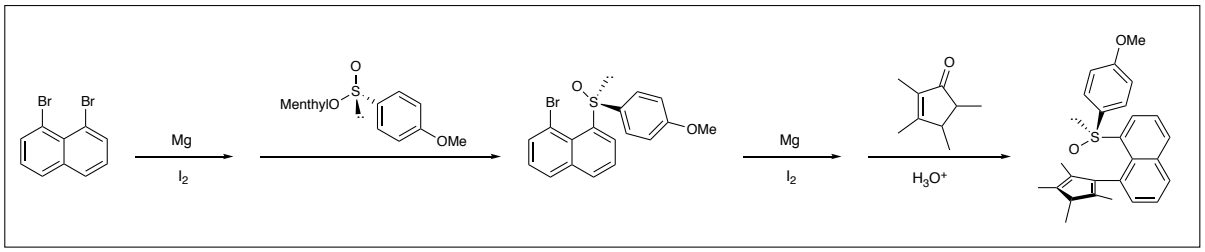
Scheme 4: Mechanistic study for allylic C-H alkylation with silver hexafluoroantimonate

These results mean that the silver and the rhodium are both capable of acting as a Lewis acid to catalyze the substitution of the allylic acetate in either an S_N1 or S_N2 mechanism, which is similar to results shown for our allylic amination studies. Overall, in other mechanistic studies in the proposed mechanism for allylic C-H amination it was found to most likely favor an S_N1 mechanism due to the formation of the highly stabilized benzyl allyl cation. Therefore, since the system for allylic C-H alkylation is very similar to the allylic C-H amination we can conclude that most likely our mechanism is similar to that of allylic C-H amination and is most likely proceeding through an S_N1 reaction.

Development of Chiral Catalyst

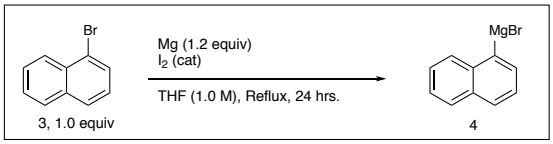
The synthesis of the chiral sulfoxide cyclopentadienyl ligand proposed was to first do a magnesium/halogen exchange of 1,8-dibromonapthalene and addition into a menthyl sulfinate

ester to obtain the sulfoxide part of the ligand (Scheme 5).[15-16] Then a Grignard of the sulfoxide would be made and a Grignard reaction with tertamethylcyclopent-2-enone would be done to form the final ligand, which would then be complex onto rhodium.



Scheme 5: Proposed synthesis of chiral sulfoxide cyclopentadienyl ligand

Therefore to begin this synthesis conditions for making a naphthalene Grignard from 1-bromonapthelene and then doing a Grignard reaction with tertamethylcyclopent-2-enone had to be determine. First a 1.0 M synthesis of the naphthalene Grignard reaction was done under the conditions (Scheme 6).

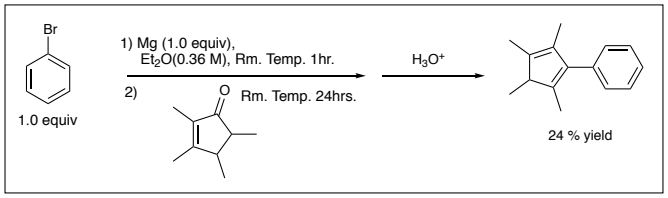


Scheme 6: Synthesis of Naphthalene Grignard reagent

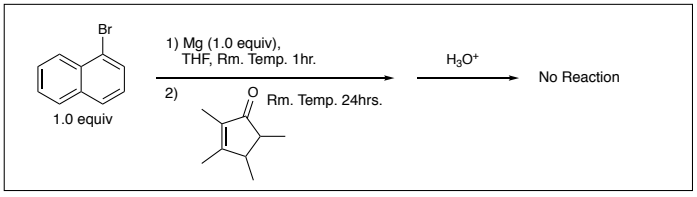
When the naphthalene Grignard (4) was cannulated from the reaction round bottom to a new round bottom to store the reagent it was observed towards the end of cannulation that a solid formed in the solution. Later, the Grignard (4) was titrated with a solution of lithium chloride in THF.[17] A larger amount of the Grignard than would be necessary to titrate a 1.0 M solution was needed in order to change the color of the lithium chloride solution therefore the Grignard synthesized was a significantly lower concentration then expected. It was determined

that solid formation in the Grignard solution was a result of too high of a concentration and maybe a lower concentration would lead to no solid crashing out of the solution. Therefore, the synthesis of the naphthalene Grignard was achieved by diluting the reaction to 0.25 M-0.30 M (Scheme 6). The Grignard (4) was synthesized at a 0.27 M concentration and there was no solid that formed in the solution when it was cannulated.

It was found in the literature that there is a one-pot method for the synthesis of 2,3,4,5-tertamethylcyclopenta-1,5-dien-1-yl)benzene ligand (Scheme 7).[18-19] These reaction conditions were recreated and obtained a yield of 24%. The experiment was then conducted using bromonaphthalene in THF and was found to be unsuccessful with initial attempts (Scheme 8).



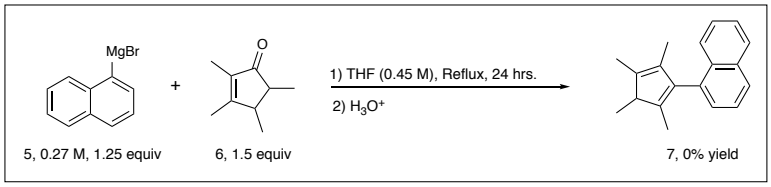
Scheme 7: One-pot synthesis of cyclopentadienyl benzene ligand



Scheme 8: One-pot synthesis of cyclopentadienyl naphthalene ligand.

Therefore, the reaction was reattempted for bromonaphthalene using diethyl ether as the solvent, longer reaction time, and even adding iodine to catalyze the Grignard formation and none of these aided in observing any desired product. The one pot method was then abandoned and prepared naphthalene Grignard was used (Scheme 9). This reaction was ran

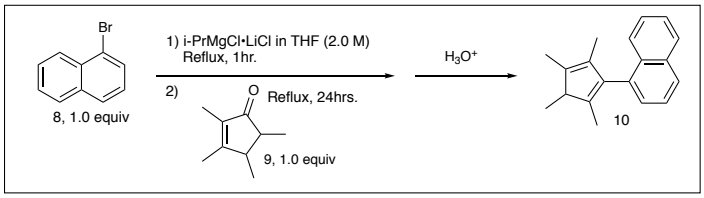
several times and it appeared as if product (7) was possibly made by ^{1}H NMR but was not certain since the peaks for methyl groups on the cyclopentene of the product and the starting material seemed to be very close. TLC of the reaction revealed incomplete consumption of the starting material with evidence of a new product. Purification proved to be very challenging since the product is very nonpolar and lead to no isolated product.



Scheme 9: Synthesis of cyclopentadienyl naphthalene ligand from the naphthalene Grignard

Before attempting to scale up the reaction for a distillation a sample of the crude reaction mixture was observed by liquid chromatography mass spectrometry (LC-MS). There was one mass found in the sample from this method corresponding to tetramethylcyclopent-2-enone. Therefore, most of the crude reaction mixture contained the tetramethylcyclopent-2-enone and the new product spot from TLC that I was trying to isolate must only be in a very small quantity if it could not be picked up by LC-MS. Since reactions with the naphthalene Grignard was not able to achieve the desired product it was then determined to try a turbo-Grignard instead. The idea to move to a turbo-Grignard is that it will make the naphthalene Grignard reagent to be more nucleophillic and will hopefully be able to achieve attacking the tertamethylcyclopent-2-enone to obtain the desired product. The naphthalene turbo-Grignard reagent was synthesized under the conditions (Scheme 10).[20] It appears by ^{1}H NMR that the desired product has been synthesized however there is still excess tertamethylcyclopent-2-

enone in the reaction mixture. The separation of the desired product from the reaction mixture is still being investigated.



Scheme 10: One-pot synthesis of cyclopentadienyl naphthalene ligand from the naphthalene turbo-Grignard

Conclusions and Future Directions

Although the allylic C-H alkylation method did not provided a wide scope of nucleophiles that tolerated these conditions there were still five that worked successfully in moderate to high yields. It was found that the nucleophiles that were tolerated in the system were ones that contained one nitro, ketone, or ester group and ones that had two ester groups. The highest yielding nucleophile contained a nitro and ketone group well the lowest contained two benzyl ester groups. The regioselectivity of this method was also probed by using unsymmetrical substrates that were β-alkyl-styrene derivatives with a variety of the best nucleophiles form the reaction scope with diphenylpropene. These reactions with the β-alkyl-styrene derivatives probed were unsuccessful most likely due to the unknown energy level between the benzyl allyl cation and the equilibrium to generate the active nucleophiles. However, more studies would have to be down to determine which factor influences the mechanism of the reaction most. Past investigations in the Blakey group have concluded the mechanism for allylic C-H amination with diphenylpropene goes through a π-allyl intermediate where an oxidation happens to exchange the ligand to release the allylic acetate. The allylic acetate is then converted to the

allylic amine by a Lewis acid catalyzed substitution where the data favors an S_N1 type of reaction. Therefore in order to explain our results mechanistic studies were done with diphenylallyl acetate and dimethylmalonate to find out if the allylic C-H alkylation went through the same mechanism as allylic C-H amination. These mechanistic studies were done with just using rhodium or silver to catalyze the reaction and it was found that both produced product as also observed in the studies of allylic amination. Therefore, it seems that the allylic alkylation goes through a similar mechanism where the S_N1 reaction is more likely. This explains why the diphenylpropene work as a better substrate than the styrene derivatives because it has the ability to form a more stabilized benzyl allyl cation than the styrene derivatives. Overall, this project has been completed to what the original goals were, however development of a second-generation system would be encouraged to hopefully achieve a greater reactivity with many different nucleophiles as well as be able to tolerate unsymmetrical substrates.

The development of the chiral sulfoxide cyclopentadienyl ligand has been challenging with trying to attempt to form a 2,3,4,5-tertamethylcyclopenta-1,5-dien-1-yl)naphthalene ligand first from a Grignard reaction. It was concluded after one-pot and two step synthesis that the Grignard reactions were not obtaining the desired product. Therefore a naphthalene turbo-Grignard is now being investigated to hopefully obtain the desired product. Once conditions for the 2,3,4,5-tertamethylcyclopenta-1,5-dien-1-yl)naphthalene ligand have been created they should be able to be translated over to obtain the sulfoxide cyclopentadienyl ligand. After synthesizing the ligand it will then be complexed onto the rhodium to achieve the desired chiral catalyst. The catalyst will then be tested in many amination reactions to see if it is able to obtain good enantio- and regioselectivity.

Supplemental Information

General Information

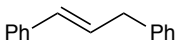
Materials: Reagents were purchased from commercial sources (Sigma Aldrich, Oakwood, Alfa Aesar, Fluka, and Fischer scientific) and were used as received unless otherwise stated. DCE was purified via distillation over CaH_2, and other anhydrous solvents were purified through alumina using a Glass Contours solvent purification system. Solvents used in workup, extraction and column chromatography were used as received from commercial suppliers without further purification. All reactions and prepared solutions were conducted using anhydrous solvents in oven-dried and nitrogen charged glassware.

Analysis: ^{1}H and ^{13}C NMR spectra were taken on either a Varian Inova 600 spectrometer (600 MHz ^{1}H, 150 MHz ^{13}C), Varian INOVA 500 spectrometer (500 MHz ^{1}H, 125 MHz ^{13}C), Varian Inova 400 spectrometer (400 MHz ^{1}H, 100 MHz ^{13}C), Varian VNMRS 400 spectrometer (400 MHz ^{1}H, 100 MHz ^{13}C), or Mercury 300 PLUS (300 MHz ^{1}H, 75 MHz ^{13}C) at room temperature in $CDCl_3$ (neutralized and dried using anhydrous K_2CO_3 with internal $CHCl_3$ as the reference (7.26 ppm for ^{1}H and 77.16 ppm for ^{13}C), unless otherwise stated. Chemical shift values (δ) were reported in parts per million (ppm) and coupling constants (J values) in Hz. Multiplicity was indicated using the following abbreviations: s=singlet, d=doublet, t=triplet, q=quartet, m=multiplet. Infrared (IR) spectra were taken using a Thermo Electron Corporation Nicolet 380 FT-IR spectrometer. High-resolution mass spectra were obtained using a Thermo Electron Corporation Finigan LTQFTMS (at the Mass Spectrometry Facility, Emory University). Analytical thin layer chromatography (TLC) was preformed on pre-coated glass backed EMD 0.25 mm

silica gel 60 plates. The visualization of the plates was done with UV light, p-anisaldehyde, $KMnO_4$, CAM, or PMA. Flash column chromatography was carried out using Silicycle SilaFlash F60 silica gel (40-63 microm).

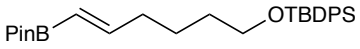
Material Preparation

1,3-diphenyl propene



In a round bottom flask, phenylacetaldehyde (5.0 g, 41.6 mmol), potassium hydroxide pellets (2.6 g, 45.8 mmol), ethanol (139 ml), and a magnetic stir bar were combined. The mixture was heated to 80°C, stirred, and refluxed for 24 hours. The mixture was concentrated in vacuo, dissolved in water and extracted three times with ethyl acetate. The organic layers were combined, washed with brine, and dried over magnesium sulfate. The crude mixture was purified by flash chromatography hexanes and EtOAc to yield a yellow oil (0.91 g, 23 % yield). The compound exhibited identical ^{1}H NMR data to previous reports. **^{1}H NMR** (400 MHz, CDCl3): δ 7.36-7.17 (m, 10H), 6.45 (d, J= 15.8 Hz, 1H), 6.35 (dt, J= 15.7, 6.6 Hz, 1H), 3.54 (d, J= 6.5 Hz, 1H) ppm.

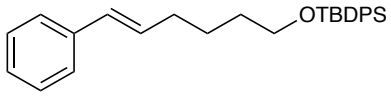
(E)-tert-butyldiphenyl((6-(4,4,5,5-tetramethyl-1,3,2-dioxaborlan-2-yl)hex-5-en-1-yl)oxy)silane



In an oven dried 250 ml two-neck round bottom flask equipped with a magnetic stir bar was weighted tert-butyl(hex-5-yn-1-yloxy)diphenylsilane (3.4 g, 10.0 mmol). The 2-neck round bottom flask was then fitted with a reflux condenser and sealed with rubber septa. The

atmosphere within was exchanged under vacuum with nitrogen to establish an inert atmosphere. The alkyne was then dissolved in THF (14.3 ml) followed by the addition of neat catechol borane (1.4 ml, 13.0 mmol). The resulting solution was then heated to reflux and stirred for 24 hours. The solution was then cooled to room temperature. An air free solution of pinacol (1.8 g, 15.0 mmol) in THF (37.5ml) was prepared and added to the reaction mixture, which was then stirred at room temperature for 24 hours. The crude reaction mixture was then diluted with EtOAc (35 ml) and washed with a 50:50 mixture of brine and DI water. The aquesous layer was extracted from EtOAc (2 x 35 ml). The combined organic layers were washed with saturated brine (ml), dried with magnesium sulfate, and concentrated to afford a crude clear yellow liquid oil. The oil was purified by flash column chromatography using hexanes: Et_2O (100:0 -> 90:10) to afford the title compound as a light yellow oil (1.4 g, 29% yield). The compound exhibited identical ^{1}H NMR data to previous reports. **^{1}H NMR** (400 MHz, CDCl3): δ 7.66-7.62 (m, 4H), 7.40-7.34 (m, 6H), 6.61 (dt, J= 18.0, 6.2 Hz, 1H), 5.41 (dt, J= 18.0, 1.6 Hz, 1H), 3.63 (t, J= 6.1 Hz, 2H), 2.17-2.13 (m, 2H), 1.60-1.49 (m, 4H), 1.02 (s, 9H) ppm.

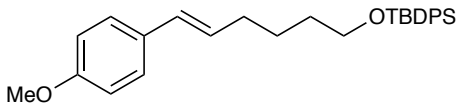
(E)-tert-butyldiphenyl((6-phenylhex-5-en-1-yl)oxy)silane



Inside an N_2 atmosphere glovebox, and oven-dried 25 ml 2-neck round bottom flask equipped with a magnetic stir bar was charged with $Pd(PPh_3)_4$ (125mg, 0.11 mmol). The flask was then sealed with rubber septa and removed from the glovebox. A solution of (E)-tert-butyldiphenyl((6-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)hex-5-en-1-yl)oxy)silane (1.5 g,

3.23 mmol) was prepared under inert atmosphere in 1,2-dimethoxyethane (3.2 ml). The solution of alkenyl-borane was then transferred to the 2-neck round bottom flask containing the $Pd(PPh_3)_4$ followed by subsequent addition of bromobenzene (0.23 ml, 2.16 mmol) and a 2M solution of K_2CO_3 (3.0 ml, 6.03 mmol). The resulting mixture was refluxed and stirred for 24 hours. The reaction mixture was cooled to room temperature and a 50:50 mixture of saturated brine and DI water (40 ml) was used as the aqueous layer and ethyl acetate was used to extract the organic components (3 x 30 ml). The combined organic layers were washed with saturated brine and dried with magnesium sulfate to afford a crude dark oil. The oil was then purified by flash column chromatography using Hexanes: Et2O (100:0 -> 90:10) to afford the title compound as a clear oil (0.736 g, 82% yield). The compound exhibited identical ^{1}H NMR data to previous reports. **^{1}H NMR** (400 MHz, CDCl3): δ 7.70-7.65 (m, 4H), 7.45-7.28 (m, 10H), 7.21 (t, J= 6.9 Hz, 1H), 6.36 (d, J= 15.8 Hz, 1H), 6.20 (dt, J= 15.8, 6.7 Hz, 1H), 3.68 (t, J= 6.2 Hz, 2H), 2.20 (q, J= 7 Hz, 2H), 1.65-1.52 (m, 4H), 1.03 (s, 9H) ppm.

(E)-tert-butyl((6-(4-methoxyphenyl)hex-5-en-1-yl)oxy)diphenylsilane



Inside an N_2 atmosphere glovebox, and oven-dried 25 ml 2-neck round bottom flask equipped with a magnetic stir bar was charged with $Pd(PPh_3)_4$ (91.3 mg, 0.08 mmol). The flask was then sealed with rubber septa and removed from the glovebox. A solution of (E)-tert-butyldiphenyl((6-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)hex-5-en-1-yl)oxy)silane (1.1 g, 2.37 mmol) was prepared under inert atmosphere in 1,2-dimethoxyethane (2.9 ml). The

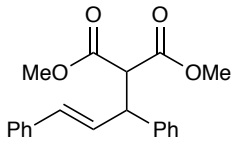
solution of alkenyl-borane was then transferred to the 2-neck round bottom flask containing the $Pd(PPh_3)_4$ followed by subsequent addition of 4-bromoanisole (0.20 ml, 1.58 mmol) and a 2M solution of K_2CO_3 (2.2 ml, 4.42 mmol). The resulting mixture was refluxed and stirred for 24 hours. The reaction mixture was cooled to room temperature and a 50:50 mixture of saturated brine and DI water (30 ml) was used as the aqueous layer and ethyl acetate was used to extract the organic components (3 x 20 ml). The combined organic layers were washed with saturated brine and dried with magnesium sulfate to afford a crude oil. The oil was then purified by flash column chromatography using Hexanes: Toluene (90:10 -> 60:40) to afford the title compound as a clear oil (0.511 g, 73% yield). The compound exhibited identical ^{1}H NMR data to previous reports. **^{1}H NMR** (400 MHz, CDCl3): δ 7.67-7.65 (m, 4H), 7.43-7.34 (m, 6H), 7.28 (d, J= 8.5 Hz, 2H), 6.83 (d, J= 8.1 Hz, 2H), 6.29 (d, J= 15.8 Hz, 1H), 6.04 (dt, J= 15.8, 6.9 Hz, 1H), 3.79 (s, 3H), 3.67 (t, J= 6.2 Hz, 4H), 2.16 (q, J= 7 Hz, 2H), 1.62-1.50 (m, 4H), 1.04 (s, 9H) ppm.

General Procedure: Optimization of C-H Alkylation with Dimethyl Malonate

Inside an N_2-filled glovebox, an oven-dried 7mL vial equipped with a magnetic stir bar was filled with silver hexafluoroantimonate, silver acetate, and $[RhCp^*Cl_2]_2$. After the solids were appropriately weighed, the reaction vial was sealed with a Teflon septum cap and removed from the glovebox. In a separate oven-dried 7mL vial, capped with a Teflon septum, a 0.40M solution of *trans*-1,3-diphenylpropene dissolved in anhydrous 1,2-dichloroethane was prepared under an inert N_2-atmosphere. Prior to evacuating the atmosphere, 0.25 equivalents of 1,4-dinitrobenzene were added to serve as an internal standard. In another separate oven-dried 7mL vial, capped with a Teflon septum, a solution of 1.5 times the necessary molar equivalents

of dimethyl malonate dissolved in anhydrous 1,2-DCE was prepared under an inert N_2-atmosphere. After the preparation of the solutions, 1mL of each was added to the reaction vial containing the solids. The reaction vial, still under an inert N_2-atmosphere maintained by an N_2-filled balloon, was allowed to heat at the appropriate temperature for the appropriate amount of time. After the allotted time, the reaction vial was exposed to air and filtered through a plug of celite, which was rinsed with 15mL of DCM. The filtrate was concentrated under reduced pressure and analyzed by ^{1}H NMR.

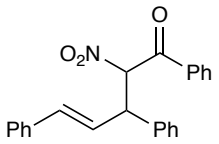
Dimethyl (*E*)-2-(1,3-diphenylallyl)malonate (2a)



Inside an N_2 atmosphere glovebox, to an oven-dried 7 mL vial equipped with a magnetic stir bar was added $[RhCp^*Cl_2]_2$ (5.0 mg, 0.0081 mmol), silver tetrafluoroantimonate (V) (12.0 mg, 0.0349 mmol), and silver acetate (140.1 mg, 0.8394 mmol). After all solids were weighed, the reaction vial was fitted with a septum cap and removed from the glovebox. In a separate oven-dried vial fitted with a septum cap, under N_2 atmosphere, a stock solution of trans-1,3-diphenylpropene (113.7 mg, 0.59 mmol) anhydrous 1,2-DCE (1.48 mL) was prepared. In another oven-dried vial filled with a septum cap, under N_2 atmosphere a solution of dimethyl malonate (130.79 mg, 0.113 ml, 0.99 mmol) in anhydrous 1,2-DCE (1.50 ml). A 1 ml aliquot was taken from each solution and added to the 7 ml vial with the solids from the glovebox. The resulting mixture was heated to 80 °C and stirred for 24 hours under an N_2 atmosphere. After cooling to room temperature, the crude mixture was filtered over celite. The celite was rinsed with DCM

(15 mL) and the combined filtrate was concentrated under reduced pressure. The crude mixture was then purified by flash chromatography on silica gel in a gradient of Toluene:Et_2O (98:2 -> 95:5) to provide the title compound as a yellow oil (82.4 mg, 64% yield). The compound exhibited identical ^{1}H NMR data to previous reports. **^{1}H NMR** (400 MHz, CDCl3): δ 7.34-7.18 (m, 10H), 6.48 (d, J= 15.78 Hz, 1H), 6.33 (dd, J= 15.70, 8.58 Hz, 1H), 4.27 (dd, J=10.87, 8.63 Hz, 1H), 3.95 (d, J= 10.92 Hz, 1H), 3.71 (s, 3H), 3.52 (s, 3H) ppm.

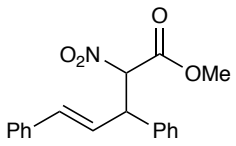
(*E*)-2-nitro-1,3,5-triphenylpent-4-en-1-one (2b)



Inside an N_2 atmosphere glovebox, an oven-dried 7 mL vial equipped with a magnetic stir bar was added $[RhCp^*Cl_2]_2$ (3.2 mg, 0.0052 mmol), silver hexafluoroantimonate (V) (9.0 mg, 0.026 mmol), and silver acetate (95.6 mg, 0.57 mmol). After all solids were weighed, the reaction vial was fitted with a septum cap and removed from the glovebox. In a separate oven-dried vial fitted with a septum cap, under N_2 atmosphere, a stock solution of trans-1,3-diphenylpropene (77.3 mg, 0.398 mmol) in 1,2-DCE (1.07 mL) was prepared. In another oven-dried vial fitted with a septum cap, under N_2 atmosphere, a solution of benzoylnitromethane (176.7 mg, 1.07 mmol) in anhydrous 1,2-DCE (1.07 ml). An aliquot of the each solution (1.0 mL) was transferred to the vial containing the solid reagents. The resulting mixture was heated to 80 °C and stirred for 24 hours under an N_2 atmosphere. After cooling to room temperature, the crude mixture was filtered over celite. The celite was rinsed with DCM (15 mL) and the combined filtrate was concentrated under reduced pressure. The crude mixture was then purified by flash

chromatography on silica gel in a gradient of Toluene:Et_2O (98:2 -> 95:5) to provide the title compound as a yellow oil (88.79 mg, 97% yield) as a 1:1 mixture of two diastereoisomers. **Rf** = 0.78 in 95:5 Toluene:Et_2O. **^{1}H NMR** (600 MHz, CDCl3): δ 8.04 (d, J= 7.34 Hz, 2H), 7.84 (d, J = 7.35 Hz, 2H), 7.65-7.05 (m, 26 H), 6.60 (dd, J = 15.8, 10.8 Hz, 2H), 6.41 (td, J= 15.7, 4.8 Hz, 2H), 6.05 (dd, J= 15.7, 8.5 Hz, 2H), 4.77 (m, 2H) ppm. **^{13}C NMR** (126 MHz, CDCl3) δ 187.5, 186.8, 137.6, 136.8, 136.2, 136.1, 134.9, 134.7, 134.5, 134.4, 133.9, 129.2, 129.1, 129.09, 129.04, 128.97, 128.8, 128.5,128.4, 128.3, 127.99, 127.94, 127.75, 126.6, 126.3, 125.8, 125.2, 91.4, 90.9, 50.45, 50.3 ppm. **HRMS** (+ p NSI): Calculated for $C_{23}H_{19}NO_3$ $[M+Na]^+$ 380.12571, observed 380.12562. **IR** (thin film): 3061, 3029, 1694, 1652, 1554, 1358, 693 cm^{-1}.

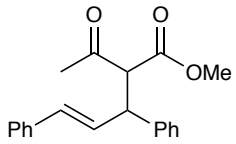
Methyl (*E*)-2-nitro-3,5-diphenylpent-4-enoate (2c)



Inside an N_2 atmosphere glovebox, to an oven-dried 7 mL vial equipped with a magnetic stir bar was added $[RhCp^*Cl_2]_2$ (3.1 mg, 0.005 mmol), silver hexafluoroantimonate (V) (5.5 mg, 0.016 mmol), and silver acetate (70 mg, 0.42 mmol). After all solids were weighed, the reaction vial was fitted with a septum cap and removed from the glovebox. In a separate oven-dried vial fitted with a septum cap, under N_2 atmosphere, a stock solution of trans-1,3-diphenylpropene (117 mg, 0.60 mmol) and methyl nitroacetate (0.28 ml, 3.00 mmol) in dichloromethane (3.0 mL) was prepared. An aliquot of the stock solution (1.0 mL, 39 mg, 0.200 mmol) was transferred to the vial containing the solid reagents. The resulting mixture was heated to 80 °C and stirred for 24 hours under an N_2 atmosphre. After cooling to room temperature, the crude mixture was

filtered over celite. The celite was rinsed with EtOAc (7 mL) and the combined filtrate was concentrated under reduced pressure. The crude mixture was then purified by flash chromatography on silica gel in a gradient of Hexanes:EtOAc (95:5 -> 0:100) to provide the title compound as a yellow oil (48 mg, 76% yield) as a 1:1 mixture of two diastereoisomers. **Rf** = 0.32 in 85:15 Hexanes:EtOAc. **^{1}H NMR** (600 MHz, CDCl3): δ 7.37 – 7.23 (m, 20H), 6.56 (d, J = 15.7 Hz, 2H), 6.38 (dd, J = 15.7, 8.7 Hz, 1H), 6.25 (dd, J = 15.7, 9.0 Hz, 1H), 5.55 (t, J= 11.0 Hz, 2H), 4.52 (dt, J= 20.5, 10.1 Hz, 2H), 3.79 (s, 3H), 3.61 (s, 3H) ppm. **^{13}C NMR** (126 MHz, CDCl3) δ 163.7, 163.2, 137.3, 136.7, 136.1 129.2, 129.1, 128.6, 128.5, 128.2, 128.1, 128.09, 128.07, 128.06, 127.7, 126.6, 126.5, 125.3, 124.9, 91.7, 91.2, 53.6, 53.4, 50.5, 50.3, 29.7 ppm. **HRMS** (+ p NSI): Calculated for $C_{18}H_{17}NO_4$ $[M+Na]^+$ 334.10510, observed 334.10498. **IR** (thin film); 2923, 2853, 1751, 1558, 743, 694 cm^{-1}.

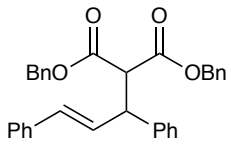
Methyl (*E*)-2-acetyl-3,5-diphenylpent-4-enoate (2d)



Inside an N_2 atmosphere glovebox, to an oven-dried 7 mL vial equipped with a magnetic stir bar was added $[RhCp^*Cl_2]_2$ (2.5 mg, 0.004 mmol), silver tetrafluoroantimonate (V) (5.5 mg, 0.16 mmol), and silver acetate (70 mg, 0.42 mmol). After all solids were weighed, the reaction vial was fitted with a septum cap and removed from the glovebox. In a separate oven-dried vial fitted with a septum cap, under N_2 atmosphere, a stock solution of trans-1,3-diphenylpropene (117 mg, 0.60 mmol) and methyl acetoacetate (0.03 ml, 0.30 mmol) in dichloromethane (1.5 mL) was prepared. An aliquot of the stock solution (1.0 mL, 78 mg, 0.40 mmol) was transferred

to the vial containing the solid reagents. The resulting mixture was heated to 80 °C and stirred for 24 hours under an N_2 atmosphere. After cooling to room temperature, the crude mixture was filtered over celite. The celite was rinsed with EtOAc (7 mL) and the combined filtrate was concentrated under reduced pressure. The crude mixture was then purified by flash chromatography on silica gel in a gradient of Hexanes:EtOAc (97:3 -> 80:20) to provide the title compound as a yellow oil (53 mg, 87% yield) as a 1:1 mixture of two diastereoisomers. The compound exhibited identical ^{1}H NMR data to previous reports. **Rf** = 0.22 in 90:10 Hexanes:EtOAc. **^{1}H NMR** (400 MHz, CDCl3): δ 7.32-7.18 (m, 20H), 6.45 (d, J= 11.9 Hz, 1H), 6.41 (d, J= 11.9 Hz, 1H), 6.27 (dd, J=13.0, 5.6 Hz, 1H), 6.22 (dd, J=13.0, 5.6 Hz, 1H), 4.28 (dd, J= 8.3, 3.0 Hz, 1H), 4.26 (dd, J= 8.3, 3.0 Hz, 1H), 4.11 (d, J= 9.6 Hz, 1H) 4.08 (d, J = 9.6 Hz, 1H), 3.67 (s, 3H), 3.47 (s, 3H), 2.28 (s, 3H), 2.01 (s, 3H) ppm.

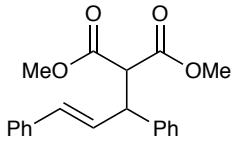
Dibenzyl (E)-2-(1,3-diphenylallyl)malonate (2e)



Inside an N_2 atmosphere glovebox, an oven-dried 7 mL vial equipped with a magnetic stir bar was added $[RhCp^*Cl_2]_2$ (3.2 mg, 0.0052 mmol), silver hexafluoroantimonate (V) (7.1 mg, 0.021 mmol), and silver acetate (90.1 mg, 0.54 mmol). After all solids were weighed, the reaction vial was fitted with a septum cap and removed from the glovebox. In a separate oven-dried vial fitted with a septum cap, under N_2 atmosphere, a stock solution of trans-1,3-diphenylpropene (88.9 mg, 0.456 mmol) in 1,2-DCE (1.14 mL) was prepared. In another oven-dried vial fitted with a septum cap, under N_2 atmopshere, a solution of dibenzylmalonate (274.0 mg, 0.964 mmol) in

anhydrous 1,2-DCE (0.96 ml). An aliquot of the each solution (0.64 mL) was transferred to the vial containing the solid reagents. The resulting mixture was heated to 80 °C and stirred for 24 hours under an N_2 atmosphre. After cooling to room temperature, the crude mixture was filtered over celite. The celite was rinsed with DCM (15 mL) and the combined filtrate was concentrated under reduced pressure. The crude mixture was then purified by flash chromatography on silica gel in a gradient of Hexanes:Et_2O:Toluene (95:0:5 -> 80:15:5) to provide the title compound as a yellow oil (9.4 mg, <7% yield). **Rf** = 0.62 in 80:15:5 Hexanes:Et_2O:Toluene. The compound exhibited identical ^{1}H NMR data to previous reports. **^{1}H NMR** (400 MHz, CDCl3): δ 7.30-7.18 (m, 28H), 7.05-7.01 (m, 2H), 6.41 (d, J= 15.8 Hz, 1H), 6.29 (dd, J=15.8, 7.9 Hz, 1H), 5.09 (dd, J=12.0, 13.9 Hz, 2H), 4.91 (dd, J= 12.1, 14.0 Hz, 2H), 4.28 (dd, J= 8.3, 10.8 Hz, 1H), 4.03 (d, J= 10.9 Hz, 1H) ppm.

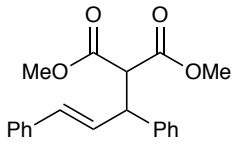
Rhodium Mechanistic Study



Inside an N_2 atmosphere glovebox, to an oven-dried 7 mL vial equipped with a magnetic stir bar was added [RhCp*$(CH_3CN)_3$]$(SbF_6)_2$ (6.7 mg, 0.008 mmol). After the solid was weighed, the reaction vial was fitted with a septum cap and removed from the glovebox. In a separate oven-dried vial fitted with a septum cap, under N_2 atmosphere, a stock solution of trans-1,3-diphenylallyl acetate (76 mg, 0.30 mmol) and dimethylmalonate (0.086 ml, 0.75 mmol) in dichloromethane (1.5 mL) was prepared. An aliquot of the stock solution (1.0 mL, 51 mg, 0.20 mmol) was transferred to the vial containing the solid reagent. The resulting mixture was

heated to 80 °C and stirred for 24 hours under an N_2 atmosphere. After cooling to room temperature, the crude mixture was filtered over celite. The celite was rinsed with EtOAc (7 mL) and the combined filtrate was concentrated under reduced pressure. The crude mixture was then purified by flash chromatography on silica gel in a gradient of Et_2O:Toluene (98:2 -> 95:5) to provide the title compound as a yellow oil (43 mg, 66% yield). The compound exhibited identical ^1H NMR data to previous reports.

Silver Mechanistic Study



Inside an N_2 atmosphere glovebox, to an oven-dried 7 mL vial equipped with a magnetic stir bar was added silver hexafluoroantimonate (V) (2.3 mg, 0.0067 mmol). After solid was weighed, the reaction vial was fitted with a septum cap and removed from the glovebox. In a separate oven-dried vial fitted with a septum cap, under N_2 atmosphere, a stock solution of 1,3-diphenylallyl acetate (86.0 mg, 0.341 mmol) in anhydrous 1,2-DCE (0.86 mL) was prepared. In another oven-dried vial filled with a septum cap, under N_2 atmosphere a solution of dimethyl malonate (99.2 mg, 0.09 ml, 0.75 mmol) in anhydrous 1,2-DCE (0.75 ml). A 0.5 ml aliquot was taken from each solution and added to the 7 ml vial with the solid from the glovebox. The resulting mixture was heated to 80 °C and stirred for 24 hours under an N_2 atmosphere. After cooling to room temperature, the crude mixture was filtered over celite. The celite was rinsed with DCM (15 mL) and the combined filtrate was concentrated under reduced pressure. The crude mixture was then purified by flash chromatography on silica gel in a gradient of Toluene:Et_2O (98:2 -> 95:5)

to provide the title compound as a yellow oil (27.9.4 mg, 43% yield). The compound exhibited identical ^{1}H NMR data to previous reports.

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