Article

(CDC)-Rhodium-Catalyzed Hydroallylation of Vinylarenes and 1,3-Dienes with Allyl Trifluoroborates.

Justin S. Marcum, Tia N. Cervarich, Rajith S Manan, Courtney C. Roberts, and Simon J. Meek

ACS Catal., **Just Accepted Manuscript** • Publication Date (Web): 22 May 2019

(CDC)-Rhodium-Catalyzed Hydroallylation of Vinylarenes and 1,3-Dienes with AllylTrifluoroborates.

Justin S. Marcum, Tia N. Cervarich, Rajith S. Manan, Courtney C. Roberts, and Simon J. Meek*

Department of Chemistry, The University of North Carolina at Chapel Hill, Chapel Hill, North Carolina 27599-3290.

Supporting Information Placeholder

ABSTRACT: Catalytic site-selective hydroallylation of vinyl arenes and 1,3-dienes is reported. Transformations are promoted by a readily accessible bidentate carbodicarbene-rhodium complex and involve commercially available allyltrifluoroborates and an alcohol. The reaction is applicable to vinyl arenes, and aryl or alkyl-substituted 1,3-dienes (30 examples). Allyl addition products are generated in 40–78% yield and in up to >98:2 site-selectivity. Reaction outcomes are consistent with the intermediacy of a Rh(III)-hydride generated by protonation of Rh(I) by an acid. A number of key mechanistic details of the reaction are presented: (1) Deuterium scrambling into the product and starting alkene indicates reversible Rh(III)–H migratory insertion. (2) A large primary kinetic isotope effect is observed. (3) With substituted allyltrifluoroborates (e.g., crotyl-BF_3K) mixtures of site isomers are generated as a result of transmetalation followed by Rh-(allyl) complex equilibration; consequently, disproving outer-sphere addition of the allyl nucleophile to Rh(III)-(η^3-allyl). (4) The stereochemical analysis of a cyclohexadiene allyl addition product supports a syn Rh(III)–hydride addition. (5) A Hammett plot shows a negative slope. Finally, utility is highlighted by a iodocyclization and cross metathesis.

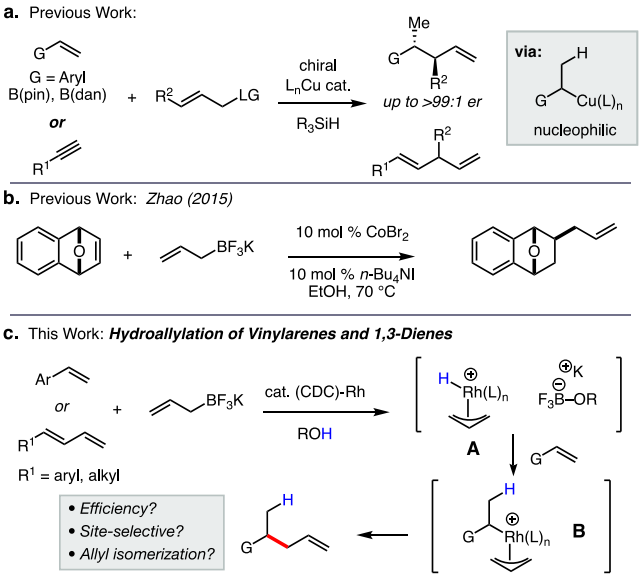
KEYWORDS: alkene, hydroallylation, carbodicarbene ligands, rhodium catalysis, allyltrifluoroborates

1. INTRODUCTION

Catalytic allyl additions to polarized C=O, and C=N π-bonds represent important C–C bond forming methods central to chemical synthesis.[1] In contrast, the closely related catalytic hydroallylations of unsaturated hydrocarbon compounds remain less well developed.[2] Such reactions are valuable as they employ simple hydrocarbon feedstocks, form a new C–C bond, and install a versatile alkene functional group. While hydroallylation represents an attractive synthetic strategy for C–C bond formation,[3] such processes have generally focused on activated C–C π-bonds (e.g., enones, dialkylidene ketones, and alkylidene malonates).[4] Accordingly, a number of efficient Ni-,[5] Pd-,[6] Cu-catalyzed[7] allyl conjugate addition methods with activated α,β-unsaturated carbonyls have been reported. Furthermore, through the appropriate choice of chiral ligands nickel-[5b-c] and copper-catalyzed[7a,d-e] reactions have been rendered highly enantioselective. In spite of these efforts, the direct hydroallylation of less activated carbon-carbon π bonds (alkenes, styrenes, dienes, allenes, alkynes) remain limited.[2] A challenge in achieving such a reaction arises from the absence of significant C–C bond polarization from an activating group. In conjugate allyl addition reactions, generally, carbon–carbon bond formation precedes C–H bond formation.

Despite these challenges, recent advances in $(L)_nCu$–H catalyzed multicomponent coupling reactions have led to the development of efficient methods for the site- and/or enantioselective hydroallylations of styrenes,[8] alkenylborons,[9] alkynes,[10] allenes,[11] and cyclopropenes[12] (Scheme 1a). In such instances reactions employ a silane as the hydride source, and proceed through a nucleophilic $(L)_nCu(I)$-alkyl intermediate that engages with an electrophilic allyl component.[13] In

Scheme 1. Catalytic Hydroallylation of Olefins.



comparison, only a single report of catalytic olefin hydroallylation that proceeds with nucleophilic allyl reagents has been disclosed. In 2015, Zhao and co-workers reported on a cobalt-catalyzed hydroallylation of heterobicyclic alkenes with allyltrifluoroborates and ethanol (Scheme 1b).[14] Under phosphine free conditions, cobalt(II)bromide catalyzes the diastereoselective hydroallylations of a variety of oxabicyclic alkenes in good yields. Notably, the authors observed

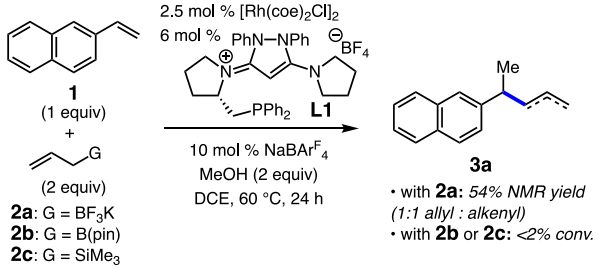
interesting divergent chemical reactivity when phosphine ligands are employed, and phosphine-cobalt species result in allylative ring-opening reactions instead.[15] Related allyl–olefin couplings via allyl C–H activation have also been reported.[16]

As part of an initiative to explore olefin hydrofunctionalization reactions catalyzed by carbodicarbene (CDC) transition metal complexes,[17] we previously discovered that the in situ metalation of CDC–bisphospine ligands by Rh(I) results in a transient Rh(III)-hydride that is able to initiate the site- and enantioselective hydroarylation of 1,3-dienes.[18] Reactions proceed via the formation of electrophilic Rh(III)-(η^3-allyl). In this regard, we hypothesized that (CDC)-Rh(III)–H species formed through oxidative protonation could be employed to effect other C–C bond forming reactions, such as catalytic hydroallylation of olefins. A key requirement for achieving olefin hydroallylation, however, is the need to for a proton source and an allyl nucleophile. Allyltrifluoroborate reagents provide an effective solution to these criteria as they are both a nucleophile, and by alcoholysis of organo trifluoroborates with an alcohol provide a controlled release of H–F.[19] A proposed mechanism for olefin hydroallylation is depicted in Scheme 1c. Transmetalation to form Rh(I)-allyl followed by oxidative protonation by H–X leads to a Rh(III)–hydride **A** that can insert across a bound olefin to form **B**. The resulting Rh(III)-alkyl complex could then undergo reductive elimination to furnish the product and regenerate the catalyst. Several pitfalls can be envisioned, most notably the protodemetalation to generate propene. The generation of metal hydrides through protonation at the metal has become an effective strategy for accessing metal hydrides for hydrofunctioanlization of 1,3-dienes.[20] For example, nucleophile additions to electrophilic metal-(η^3-allyl) species generated by M–H additions to 1,3-dienes include Ni-, Pd- and Rh-catalyzed hydroalkylation,[21] hydroamination,[22] hydroarylation,[18,23] hydrothiolation,[24] and hydrophosphinylation.[25]

Herein, we describe an efficient Rh-catalyzed intermolecular hydroallylation of vinyl arenes and 1,3-dienes that proceeds with high site-selectivity to afford the branched products in good yields. Reactions employ common olefins, commercially available allyltrifluorborates, an alcohol, and are promoted by an in situ generated (CDC)-Rh catalyst.

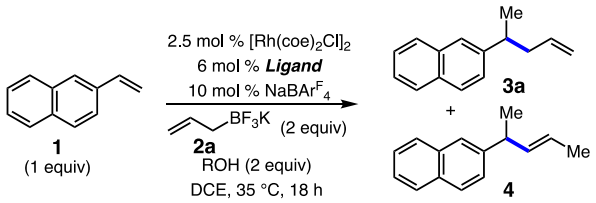
2. RESULTS AND DISCUSSION

Scheme 2. Initial Result

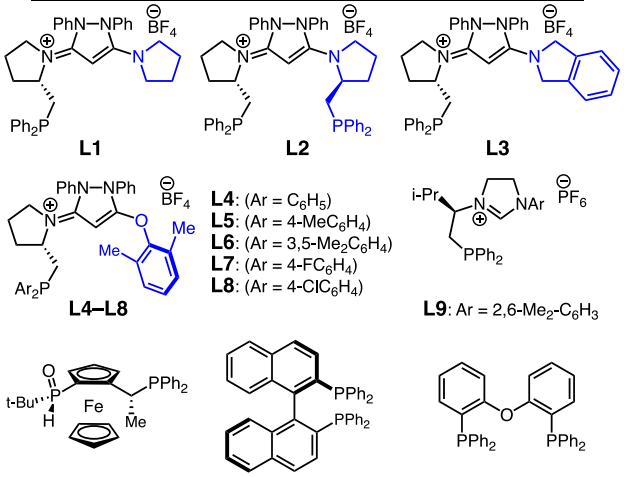


2.1. The Method and Its Scope. *2.1.1. Hydroallylation of Aryl-Substituted Alkenes.* We began our investigations by studying the reaction between 2-vinyl naphthylene **1**, and allyl reagents **2a-c** (Scheme 2). Treatment of **1** and **2a** with 5 mol % in situ generated (**L1**)-Rh in the presence of methanol in DCE at 60 °C afforded **3a** in 54% NMR yield as a 1:1 mixture of allyl and alkenyl isomers. In comparison, reaction with allyl reagents **2b** or **2c**, under identical conditions, yielded no desired product, likely due to the inability of **2b-c** to easily generate H–X through reaction with a methanol. Furthermore, control reactions with 5 or 10 mol %[$H(OEt_2)_2$][BAr^F_4] and either **2b** and

Table 1. Optimization of (CDC)-Rh-Catalyzed Hydroallylation of Vinyl Arenes.[a]



entry	Ligand	ROH	Conv (%)[b,c]	3a:4[b]
1	**L1**	MeOH	57	4:1
2	**L2**	MeOH	<2	-
3	**L1**	*i*-PrOH	58	6:1
4	**L1**	H_2O	77	6:1
5	**L3**	H_2O	74	1:1
6	**L4**	H_2O	85	8:1
7	**L5**	H_2O	80	3:1
8	**L6**	H_2O	71	6:1
9	**L7**	H_2O	80	14:1
10	**L8**	H_2O	68	10:1
11	**L9**	H_2O	25	2:1
12[e]	**L10**(S_P,*R*)-JoSPOphos	H_2O	<2	-
13	**L11** (*R*)-binap	H_2O	<2	-
14	**L12** DPEphos	H_2O	12	1:>20[d]



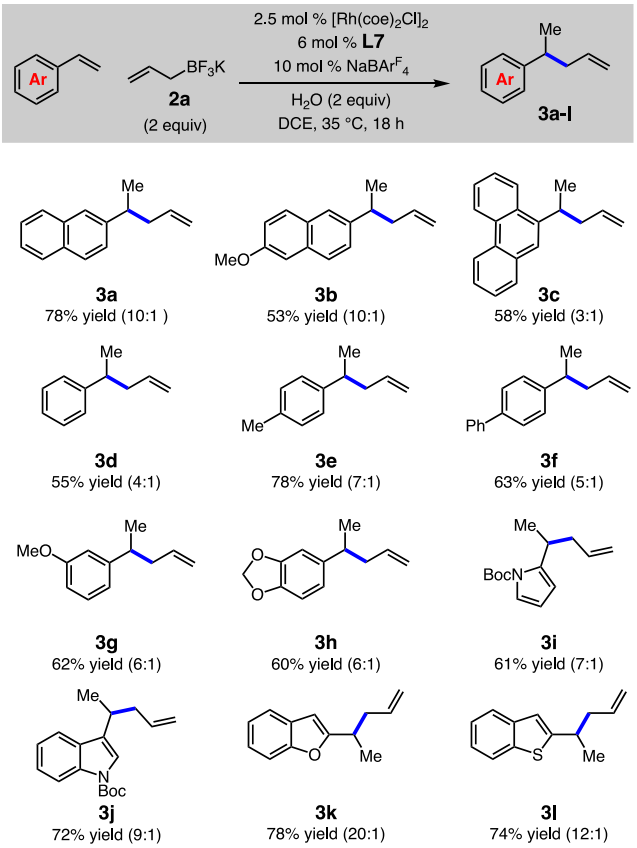
[a]Reactions performed under N_2 atmosphere. [b]Conversion to **3a** and **4** (*E* + *Z* isomers) determined by analysis of 400 or 600 MHz ^{1}H NMR spectra of crude reactions with DMF as internal standard. [c]Products formed in <60:40 er. [d]1:1 mixture of *E*:*Z* isomers. [e](S_P,*R*)-JoSPOphos = (S_P)-1-[(*R*)-*tert*-Butylphosphinoyl]-2-[(*R*)-1-(diphenylphosphino)ethyl]ferrocene.

2c resulted in <2% conversion to product and olefin polymerization.

To optimize the selectivity and efficiency of the catalytic hydroallylation reaction, a series of CDC ligands (**L1**–**L8**) were evaluated in combination with [$Rh(coe)_2Cl]_2$ (Table 1). We have previously shown that (CDC)-Rh complexes are efficiently formed in situ via rhodium C–H metalation of pyrazolium salts.[18] In this regard, initial reactions involving in situ pincer catalyst derived from tridenate **L2**, afforded <2% conversion with methanol as alcohol additive (Table 1, entry 2),

which indicated a bidentate ligand scaffold was crucial for reactivity. However, when alkene **1** and allylboron **2a** (2 equiv) are subjected to 5 mol % in situ generated (**L1**)-Rh (Table 1, entry 2), 2 equivalents of MeOH in DCE at 35 °C, 57% conversion to homoallyl naphthalene **3a** is observed in 18 h as a 4:1

Scheme 3. Scope of Vinyl Arene Hydroallylation[a–c]

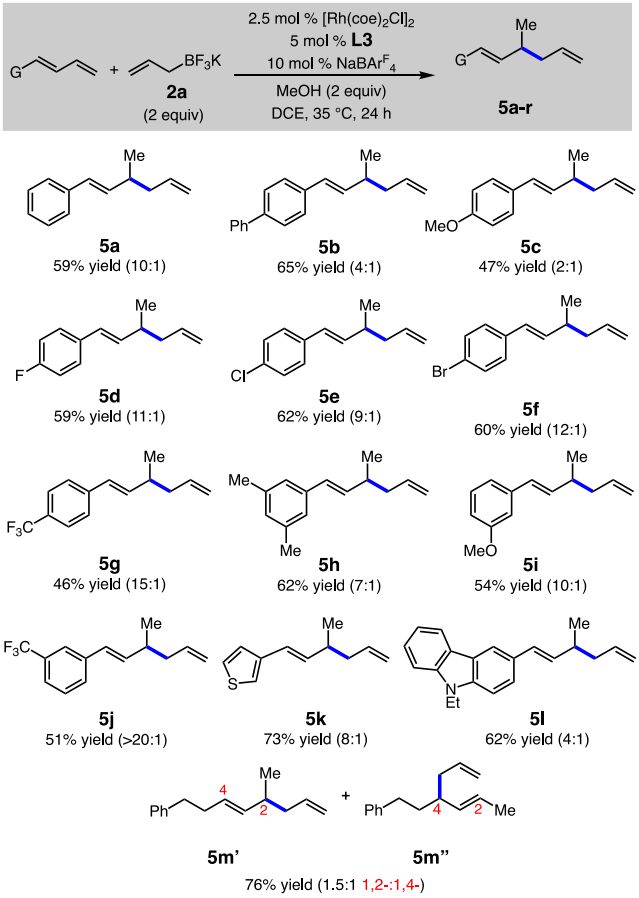


[a]Reactions were carried out under N_2 atmosphere. Conversion >98% in all cases, determined by analysis of ^{1}H spectra of unpurified product mixtures (±2%). Yields are reported as a combination of isomers (±5%); allyl/alkenyl ratio given in parentheses. [b]Experiments were run in duplicate or more. See the SI for details. [c]Ratio in parentheses corresponds to crude allyl:alkenyl isomer ratio.

mixture of allyl and alkenyl isomers. Varying the alcohol additive to *i*-PrOH and H_2O (Table 1, entries 3–4) led to an increase in reaction efficiency; in the presence of H_2O **3a** is formed in 77% conversion and decreased in isomerization (**3a**:**4** 6:1). With isoindoline (**L3**) or aryloxy (**L4**) substituted pyrazoliums (Table 1, entries 5–6) there is an increase in conversion to desired product 74% (1:1, **3a**:**4**) and 85% (8:1; **3a**:**4**), respectively. Placement of electron-donating and electron-withdrawing substituents on the diarylphosphine, **L5**–**L8** (Table 1, entries 7–10), identified (p-F-C_6H_4)$_2$P **L7** as the optimal CDC ligand furnishing **3a** in 80% NMR yield and 14:1 (**3a**:**4**). The less electron-donating phosphine likely minimizes alkene isomerization by facilitating substitution of the product from the catalyst by another alkene prior to formation of the (CDC)-Rh-hydride. Reaction with related bidentate (NHC)–phosphine **L9** (Table 1, entry 11), or chiral bidenate phosphines (S_p,R)-JoSPOphos (**L10**), and (*R*)-binap (**L11**) (Table 1, entries 12–13) resulted in minimal transformation (<25% conv). Lastly, achiral DPEphos (**L12**) (Table 1, entry 14) resulted in the selective formation to isomerized **4** in 12% conversion. It should be noted that, while chiral enantiopure CDC ligands were employed in reactions, **3a** was formed in <60:40 er in all cases.

With optimal conditions in hand we next set out to study the scope of vinyl arenes with allyltrifluoroborate **2**. The results of these studies are illustrated in Scheme 3. A wide array of vinyl arenes undergo allyl additions with 5 mol % in situ generated (**L7**)-Rh and two equivalents of allyltrifluoroborate **2** within 18

Scheme 4. Synthesis of 1,5-Dienes by Hydroallylation of 1,3-Dienes[a–c]



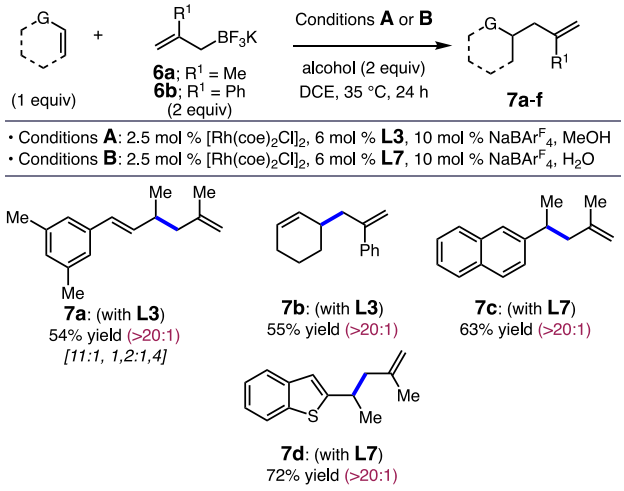
[a]Reactions were carried out under N_2 atmosphere. Conversion >98% in all cases, determined by analysis of ^{1}H spectra of unpurified product mixtures (±2%). Yields are reported as a combination of isomers (±5%); allyl/alkenyl ratio given in parentheses. [b]Experiments were run in duplicate or more. See the SI for details. [c]Ratio in parentheses corresponds to crude allyl:alkenyl isomer ratio.

hours at 35 °C (Scheme 3). Additions to naphthalene- and phenanthrene-derived vinyl substrates are efficient, and products **3a-c** are formed in 53–78% yield. Notably, while the naphthyl products were generated in 10:1 selectivity, phenanthrene-derived **3c** was formed as a 3:1 mixture of allyl:alkenyl isomers. Similarly, a variety of non-polycyclic arene olefins react efficiently. Reaction of one equivalent of alkene furnishes the allyl addition products **3d**–**3h** in 55–78% yield. The reaction protocol also extends to heteroaryl-substituted alkenes, which proceed with efficient allyl group transfer. For example, catalytic hydroallylation allows for the preparation of allyl additions products containing pyrrole (**3i**), indole (**3j**), benzofuran (**3k**), and benzothiophene (**3l**) rings in 61–78% yield, and >7:1 allyl:alkenyl isomers. Under the current protocol 1,1-disubstituted styrenes and alkyl-substituted terminal alkenes do not undergo hydroallylation.

2.1.2. Hydroallylation of 1,3- Dienes. After having demonstrated the protocol worked well for a broad selection of alkenylarenes, we investigated the applicability of the method towards reactions involving 1,3-dienes (Scheme 4). A significant feature of the Rh-catalyzed method is the modularity of the CDC ligand scaffold. Consequently, a short survey of CDC ligands and alcohol additives identified pyrazolium **L3** in combination with 2.0 equivalents of MeOH afforded more optimal results compared to **L7** and H_2O. In the presence of 2.5 mol % $[Rh(coe)_2Cl]_2$ and 6.0 mol % **L3** in DCE at 35 °C, a variety of aryl-substituted 1,3-dienes bearing electron-withdrawing and electron-donating groups undergo efficient hydroallylation in 24 h to afford 1,5-diene products (**5a**–**5j**) in 46–65% isolated yields, and >5:1 allyl:alkenyl selectivity. Similar to vinylarenes, the reaction is also tolerant of heteroaromatic substrates to afford heteroaryl-containing 1,5-dienes; the formation of thiophenene **5k** in 73% yield, and carbazole **5l** in 62% yield, are representative. Finally, under the current catalytic protocol, hydroallylation of alkyl-substituted 1,3-dienes also proceeds to high conversion, however, the products are generated as an inseparable mixture of 1,2- and 1,4-hydroallyl addition products. For example, regioisomers **5m'** and **5m"** are formed in 76% yield as 1.5:1 mixture. Phosphine–CDC ligand development is currently in progress to address challenges associated with site-selectivity.

2.1.3. Hydroallylation with 2-Substituted Allyltrifluoroborates. To increase the reaction scope, 2-allyltrifluoroborates were examined (Scheme 5). Both 2-methyl (**6a**) and 2-phenyl-substituted (**6b**) allyltrifluoroborates were prepared and employed in the hydroallylation reaction. Under the optimal reaction conditions with pyrazolium **L7** (Scheme 3, vinyl arenes) and **L3** (Scheme 4, 1,3-dienes) as ligands both organoborons reacted smoothly to provide allyl addition products **7a**–**7d** in 54–72% yield and excellent selectivity (>20:1). Notably, the formation of isomerized product is prevented owing to the increased sterics of the 1,1-disubstituted alkene. Additionally, product **7b** arising from the reaction of cyclohexadiene represents an example of an internal alkyl-substituted 1,3-diene.

Scheme 5. Catalytic Hydroallylation with 2-Substituted Allyltrifluoroborates[a–c]

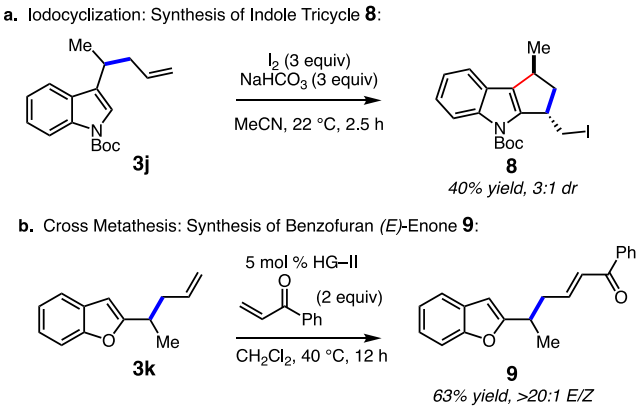


[a]Reactions were carried out under N_2 atmosphere. Conversion >98% in all cases, determined by analysis of ^1H spectra of unpurified product mixtures (±2%). Yields are reported as a combination of isomers (±5%); allyl/alkenyl ratio given in parentheses. [b]Experiments were run in duplicate or more. See the SI for details. [c]Ratio in parentheses corresponds to crude allyl:alkenyl isomer ratio.

2.1.4. Utility. The homoallyl arenes synthesized through the current hydroallylation method can be functionalized in a number of ways. Two brief examples are illustrated in Scheme 6: (1) Iodocyclization of **3j** by reaction with I_2 in MeCN at 22 °C affords tricycle **8** in 40% isolated yield, and 3:1 dr. (2) Cross metathesis of **3k** by treatment with 5 mol % Hoveyda-Grubbs-II and 2 equivalents of phenylvinylketone furnishes **9** in 63% yield and >20:1 *E/Z* selectivity).

2.3. Reaction Mechanism. *2.3.1. Deuterium Labeling Experiments.* With an effective method for hydroallylation in hand, we undertook a number of mechanistic experiments to gain insight into the (CDC)-Rh-catalyzed reaction mechanism. First, we conducted a variety of deuterium labeling experiments

Scheme 6. Functionalization of Homoallyl Arenes

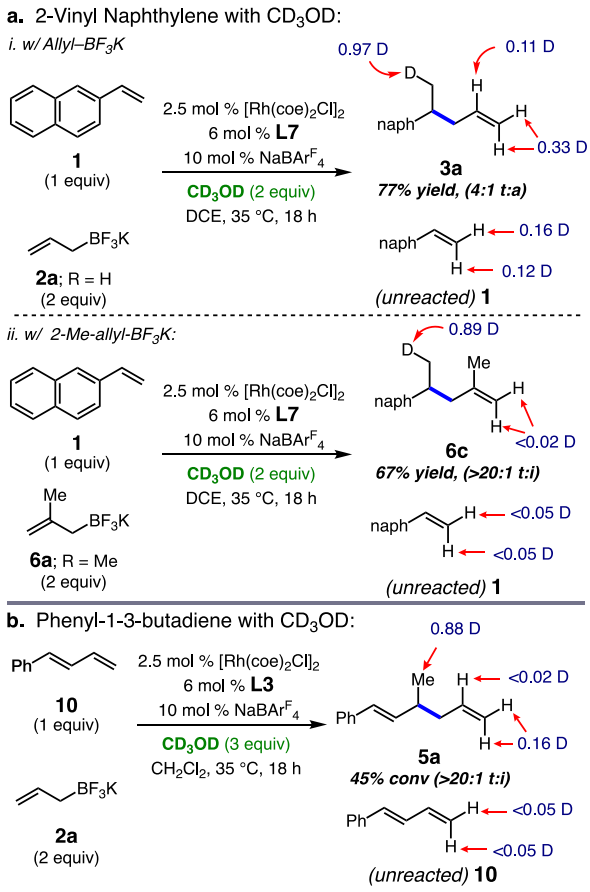


with both vinyl arene and 1,3-diene substrates. As depicted in Scheme 7a, the hydroallylation reactions of vinyl naphthalene **1**, and phenylbutadiene **10** were carried out in the presence of CD_3OD to examine deuterium scrambling into the product and starting olefins. For vinyl naphthalene, 0.97 deuterium is incorporated into the methyl group of **3a**, 0.44 deuterium in the alkene of **3a** (0.11 D internal, and 0.33 D terminal), and 0.28 deuterium (0.16 D and 0.12 D) into the terminal alkene C–H bonds of unreacted **1**. The corresponding reaction with 2-methylallyl trifluoroborate **6a** and CD_3OD furnishes **6c** in 67% yield (>20:1 selectivity), and 0.89 deuterium in the methyl group and <0.02 deuterium is exchange into terminal alkene. Notably, the unreacted alkene **1** only contains <0.05 deuterium. These data indicate the Rh-catalyst rapidly and reversibly exchanges in hydrogen/deuterium prior to C–C bond formation. While 1,3-dienes are less stable under the reaction conditions, catalytic hydroallylation of phenylbutadiene **10** with **2a** in the presence of two equivalents of CD_3OD leads to similar deuterium distributions (Scheme 7b). Reaction with 5 mol % in situ generated (**L3**)-Rh and a reaction time of 18 h, afforded **5a** in 45% NMR yield (>98% conv of **5a**) in >20:1 allyl/alkenyl selectivity with 0.88 deuterium incorporated into the methyl group. As with vinyl naphthalene **3a**, 0.16 D is deuterium is incorporated into the terminal alkene of **5a**, and <0.1 D into unreacted **10**. The slightly lower deuterium incorporation into unreacted 1,3-diene **10** (vs **3a**) is likely a result of the slower substitution of a diene from rhodium. Control reactions run with CD_3OD and without $[Rh(coe)_2Cl]_2$ do not result in deuterium incorporation into either **1** or **10** by Brønsted acid pathways.

In search of additional evidence, to further probe the hydride incorporation step, a KIE study was performed. The absence of competing alkene isomerization in the formation of **6c**, permitted the relative reaction rates between CH_3OH:CD_3OD to be established (Scheme 7c). In the catalytic reaction between **1** and **6a** and CH_3OH:CD_3OD (1:1), a k_H/k_D of 6.13 was observed indicating a large primary KIE. This likely arises from the Rh(I) protonation, however, the competition reaction does not provide information about the rate determining step.[26] The magnitude of the KIE is similar to those observed for protonation at the metal in other systems.[26] Unfortunately, attempts to obtain a KIE based on initial rates was impeded by the heterogeneity of the reactions caused by the allyltrifluoroborate.

In an effort to distinguish between the either Rh(III)–H syn migratory insertion vs outer-sphere protonation of a rhodium bound alkene mechanism,[27] the synthesis of cyclohexadiene **7b** was carried out with 2.0 equivalents of CD_3OD, and the stereochemical position of the deuterium determined (Scheme 8). Through detailed ^1H NMR analysis of **7b**, assignment and analysis of the product by ^1H NMR indicates a syn relationship between the allyl moiety and deuterium at the homoallylic position. This reaction, however, proved not conclusive due to competitive incorporation of deuterium into cyclohexadiene starting material prior to C–C bond formation (See Supporting Information for details). This data further supports that Rh(III)–H migratory insertion is fast and reversible prior to C–C bond formation.

Scheme 7. Deuterium Labeling Experiments[a-b]



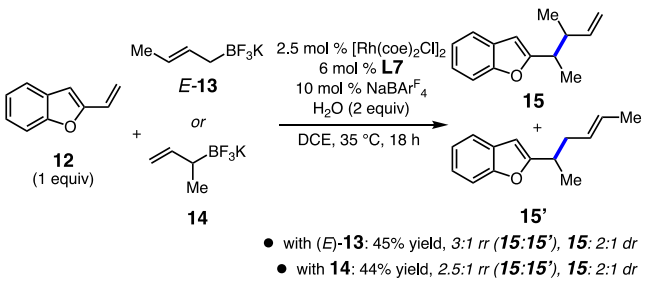
[a]Reactions were carried out under N_2 atmosphere. Conversion determined by analysis of ^1H spectra of unpurified product mixtures (±2%). Yields are reported as a combination of isomers (±5%); crude allyl/alkenyl ratio given in parentheses. [b]Experiments were run in duplicate or more. See the SI for details.

2.3.2. Reactions with Crotyl-BF_3K. In addition to reversible hydride incorporation, the isomerization of the organoboron fragment in the reaction was studied (Scheme 9). The

Scheme 8. Syn vs Anti Hydroallylation: Rh(III)–H Insertion vs Diene Protonation[a]

[a]See SI for reaction details and stereochemical assignment.

Scheme 9. Reactions with *(E)*-Crotyl-BF_3K and Reverse Crotyl-BF_3K



application of either *(E)*-crotyltrifluoroborate *E*-**13** or reverse crotyl reagent **14**, in the (CDC)-Rh-catalyzed hydroallylation of **12**, both result in similar ratio of **15**:**15'** (3:1 vs 2.5:1) irrespective of which reagent is used. This result indicates, (i) the allyl fragment arising from the trifluoroborate transfers to rhodium and rapidly isomerizes via a Rh-allyl in the reaction prior to C–C bond formation, and (ii) the allyl nucleophile addition is not outer-sphere addition to a Rh-η^3-allyl since both reagents afford the same ratio of product regioisomers. Use of the more sterically demanding prenyl-BF_3K resulted in <2% conversion, with the resulting mass balance being unreacted starting material.

2.3.3. Hammett Plot. We then investigated the electronic nature of the transition state in the product-determining step by performing a Hammett analysis of the catalytic hydroallylation of alkenylarenes (Figure 1). A plot k_H/k_X vs $\sigma+$ results in a $\rho = -0.48$ ($R^2 = 0.9422$) indicating a buildup of positive charge on the olefin in the transition state of the product-determining step. A reasonable explanation for the negative slope that is in agreement with the deuterium scrambling data and large KIE, is that a more electron-rich olefin would help facilitate oxidative protonation to form Rh(III)–H. In addition, the negative slope

is inconsistent with rhodium-hydride insertion onto the alkene. While the negative slope could also possibly be explained by reductive elimination being the product determining step, which is supported by studies by Hartwig where a similar trend was observed in reductive elimination in phosphine-Pt-diaryl complexes,[28] such a notion would be inconsistent with the large KIE.

2.3.4. Isolated (CDC)-Rh Complex. To obtain support for the intermediacy of a bidentate (CDC)-Rh complex we synthesized [(**L1**)Rh(cod)]BF_4 **16** (Scheme 10). The complex was synthesized by deprotonation of pyrazolium salt **L1** with n-BuLi at -78 °C in THF, followed by reaction with $[Rh(cod)Cl]_2$ to afford a orange-brown solid in 98% yield. While (**L1**)-Rh **16** was spectroscopically characterized ($^{31}P\{^1H\}$= 25.04 ppm (d, J_{Rh-P} = 164.85 Hz)), unfortunately the X-ray structure of which

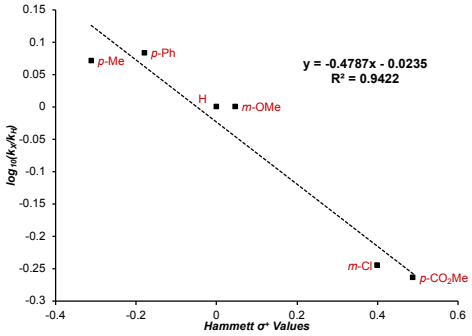
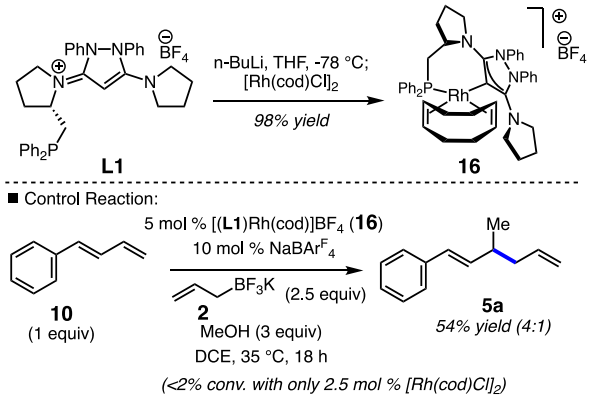


Figure 1. Plot of Log(k_X/k_H) versus Hammett σ+ values derived from the scope presented in Scheme 3 and see also SI.

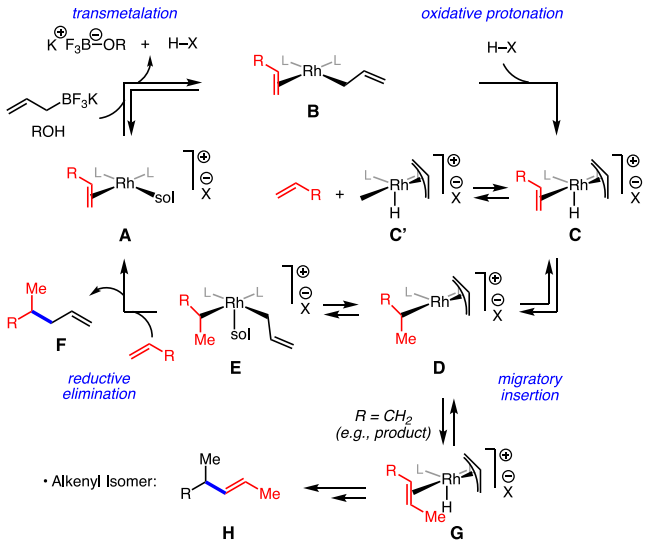
could not be obtained. Catalytic reactions with (CDC)-Rh complex **16** demonstrate that it is a competent hydroallylation catalyst (Scheme 10). Under standard conditions (see Scheme 2), with 5 mol % **16**, 1,5-diene **5a** is delivered in 54% conversion, and 4:1 allyl/alkenyl selectivity. As a control, reactions with $[Rh(cod)Cl]_2$ established that 1,5-cyclooctadiene is an ineffective ligand for promoting hydroallylation, providing support for a bidentate (CDC)-Rh as the active catalyst.

Scheme 10. Synthesis and Reactivity of [(L1)Rh(cod)]BF_4



On the basis of our mechanistic findings, we propose the catalytic cycle outlined in Scheme 11 for the catalytic olefin hydroallylation reaction. Initial in situ formation of cationic (CDC)-Rh(I) complex **A**, likely occurs via rhodium oxidative C–H metalation of the ligand followed by H–Rh–allyl reductive elimination to form propene, where the allyl arises from allyl-BF_3K. Transmetalation with allyl-BF_3K then affords Rh(I)–allyl **B**, which can undergo irreversible oxidative protonation by H–X (generated by the reaction of BF_3 and MeOH) to afford Rh(III)–hydride **C**. Subsequent, rapid reversible rhodium-hydride migratory insertion across the olefin generates **D**, which can proceed via C–C reductive elimination to afford the product and regenerate complex **A**. It should be noted that Rh–H formation prior to allyl group transmetalation is also consistent with the data. The formation of deuterated alkene recovered at the end of the reaction can be rationalized by an equilibrium between alkene complex **C** and unbound alkene complex **C'**, with the amount of deuterium incorporation related to the relative rate of dissociation of the alkene compared to reductive elimination. Low D incorporation would indicate alkene dissociation from **C** is slower than reductive elimination. Consequently, the much lower D incorporation observed in reaction of sterically more demanding 2-Me-allyl **6a** (Scheme 7a), is likely a result of increased sterics more significantly effecting

Scheme 11. Proposed Catalytic Cycle



the rate of reductive elimination versus the rate of alkene dissociation.

Finally, the observation of product alkene isomerization is expected to occur due to slow product release off the catalyst by another molecule of starting olefin. This provides opportunity for the product bound rhodium species to re-enter the catalytic cycle and generate the alkenyl isomer **H** via β-hydride elimination from **D** to afford **G**. Overall, these data point towards Rh(III)–H formation being the product-determining step.

CONCLUSION

In summary, we have developed the first catalytic site-selective hydroallyation of vinyl arenes and 1,3-dienes with allyltrifuloroborates enabled by Rh catalysts supported by new bidentate pyrazolium-based carbodicarbene ligands. This represents the first example of bidentate CDCs as effective ligands in transition metal catalysis. Catalyst is generated in situ and the reactions are efficient and proceed in good yield to afford a broad range of homoallylarenes and 1,5-diene products with high levels of olefin site-selectivity with only minimal double bond isomerization. Mechanism experiments are consistent with the intermediacy of a Rh–allyl that is formed via reversible Rh–hydride insertion on to the olefin. The highly

modular aspect of the bidentate CDCs disclosed in this study are expected to be applicable to other sets of transformations. Finally, studies aimed at expanding olefin scope, organoboron nucleophile, and developing additional chiral CDCs to render this process highly enantioselective continue to be investigated in these laboratories.

ASSOCIATED CONTENT

AUTHOR INFORMATION

Corresponding Author

*sjmeek@unc.edu.

ORCID

Simon J. Meek: 0000-0001-7537-9420
Rajith S. Manan: 0000-0001-7081-0138
Courtney C. Roberts: 0000-0001-8177-4013

Notes

Authors declare no competing financial interests.

Supporting Information

Experimental procedures, analytical data for new compounds, and NMR spectra. This material is available free of charge via the Internet at http://pubs.acs.org.

ACKNOWLEDGMENT

Financial support was provided by the NSF (CHE-1665125) and University of North Carolina at Chapel Hill. JSM is grateful for a Burroughs-Welcome fellowship from the UNC Chemistry Department. We thank the University of North Carolina's Department of Chemistry Mass Spectrometry Core Laboratory for their assistance with mass spectrometry analysis. This material is based upon work supported by the National Science Foundation under Grant No. (CHE1726291).

REFERENCES

(1) For selected reviews, see: (a) Ding, H.; Friestad, G. K. Asymmetric Addition of Allylic Nucleophiles to Imino Compounds. *Synthesis* **2005**, *2005*, 2815–2829. (b) Yus, M.; González-Gómez, J. C.; Foubelo, F. Catalytic Enantioselective Allylation of Carbonyl Compounds and Imines. *Chem. Rev.* **2011**, *111*, 7774–7854. (c) Ketcham, J. M.; Shin, I.; Montgomery, T. P.; Krische, M. J. Catalytic Enantioselective C-H Functionalization of Alcohols by Redox-Triggered Carbonyl Addition: Borrowing Hydrogen, Returning Carbon. *Angew. Chem. Int. Ed.* **2014**, *53*, 9142–9150. (d) Holmes, M.; Schwartz, L. A.; Krische, M. J. Intermolecular Metal-Catalyzed Reductive Coupling of Dienes, Allenes, and Enynes with Carbonyl Compounds and Imines. *Chem. Rev.* **2018**, *118*, 6026–6052.

(2) For selected reviews of olefin hydrofunctionalization, see: Hydrofunctionalization. In *Topics in Organometallic Chemistry*; Ananikov, V. P.; Tanaka, M., Eds.; Springer: Berlin, 2014;Vol. 343. (b) Bender, C. F.; Han, X.; Widenhoefer, R. A. Platinum-Catalyzed Hydrofunctionalization of Unactivated Alkenes with Carbon, Nitrogen and Oxygen Nucleophiles. *Chem. Commun.* **2007**, 3607–3618. (c) Zeng, X. Recent Advances in Catalytic Sequential Reactions Involving Hydroelement Addition to Carbon–Carbon Multiple Bonds. *Chem. Rev.* **2013**, *113*, 6864–6900.

(3) Hartwig, J. F. Raising the Bar for the "Perfect Reaction" *Science* **2002**, *297* (5587), 1653

(4) For examples of stoichiometric allyl conjugate additions, see: Silicon (a) Hosomi, A.; Sakurai, H. Chemistry of Organosilicon Compounds. 99. Conjugate Addition of Allylsilanes to .alpha.,.beta.-Enones. A New Method of Stereoselective Introduction of the Angular Allyl Group in Fused Cyclic .alpha.,.beta.-Enones. *J. Am. Chem. Soc.* **1977**, *99*, 1673–1675. (b) Hayashi, M.; Mukaiyama, T. A Conjugate Addition of Allylsilanes to α,β-Unsaturated Ketones Catalyzed by Trityl Perchlorate. *Chem. Lett.* **1987**, 289–292. (c) Lee, P. H.; Lee, K.; Sung, S.-Y.; Chang S. The Catalytic Sakurai Reaction. *J. Org. Chem.* **2001**, *66*, 8646–8649. Tin: (d) Hosomi, A.; Iguchi, H.; Endo, M.; Sakurai, H. Allylation Reactions By Using Allylstannanes in the Presence of a Lewis Acid. *Chem. Lett.* **1979**, 977–980. Copper: (e) House, H. O.; Wilkins, J. M. Reactions Involving Electron Transfer. 12. Effects of Solvent and Substituents Upon the Ability of Lithium Diorganocuprates to Add to Enones. *J. Org. Chem.* **1978**, *43*, 2443–2454. (f) Lipshutz, B. H.; Hackmann, C. Conjugate Addition Reactions of Allylic Copper Species Derived from Grignard Reagents: Synthetic and Spectroscopic Aspects. *J. Org. Che*m. **1994**, *59*, 7437–7444.

(5) (a) Sieber, J. D.; Liu, S.; Morken, J. P. Catalytic Conjugate Addition of Allyl Groups to Styryl-Activated Enones. *J. Am. Chem. Soc.* **2007**, *129*, 2214–2215. (b) Sieber, J. D.; Morken, J. P. Asymmetric Ni-Catalyzed Conjugate Allylation of Activated Enones. *J. Am. Chem. Soc.* **2008**, *130*, 4978–4983. (c) Brozek, L. A.; Sieber, J. D.; Morken, J. P. Catalytic Enantioselective Conjugate Allylation of Unsaturated Methylidene Ketones. *Org. Lett.* **2011**, *13*, 995–997.

(6) (a) Shaghafi, M. B.; Kohn, B. L.; Jarvo, E. R. Palladium-Catalyzed Conjugate Allylation Reactions of α,β-Unsaturated *N*-Acylpyrroles. *Org. Lett.* **2008**, *10*, 4743–4746. (b) Waetzig, J. D.; Swift, E. C.; Jarvo, E. R. Conjugate Allylation Reactions of Alkylidene Malononitriles Mediated by NHC-Ligated Palladium Catalysts. *Tetrahedron* **2009**, *65*, 3197–3201.

(7) (a) Shizuka, M.; Snapper, M. L. Catalytic Enantioselective Hosomi-Sakurai Conjugate Allylation of Cyclic Unsaturated Ketoesters. *Angew. Chem. Int. Ed.* **2008**, *47*, 5049–5051. (b) Kuang, Y.; Liu, X.; Chang, L.; Wang, M.; Lin, L.; Feng, X. Catalytic Asymmetric Conjugate Allylation of Coumarins. *Org. Lett.* **2011**, *13*, 3814–3817. (c) Yamamoto, Y.; Yamada, S.; Nishiyama, H. Copper-Catalyzed Regio- and Stereoselective Conjugate Allylation of Electron-Deficient Alkynes with Allylboronates under Mild Conditions. *Chem. – Eur. J.* **2012**, *18*, 3153–3156. (d) Meng, F.; Li, X.; Torker, S.; Shi, Y.; Shen, X.; Hoveyda, A. H. Catalytic Enantioselective 1,6-Conjugate Additions of Propargyl and Allyl Groups. *Nature* **2016**, 537, 387–393. (e) Li, X.; Meng, F.; Torker, S.;

Shi, Y.; Hoveyda, A. H. Catalytic Enantioselective Conjugate Additions of (Pin)B-Substituted Allylcopper Compounds Generated in Situ from Butadiene or Isoprene. *Angew. Chem. Int. Ed.* **2016**, *55*, 9997–10002.

(8) Wang, Y.-M.; Buchwald, S. L. Enantioselective CuH-Catalyzed Hydroallylation of Vinylarenes. *J. Am. Chem. Soc.* **2016**, *138*, 5024–5027.

(9) (a) Han, J. T.; Jang, W. J.; Kim, N.; Yun, J. Asymmetric Synthesis of Borylalkanes via Copper-Catalyzed Enantioselective Hydroallylation. *J. Am. Chem. Soc.* **2016**, *138*, 15146–15149. (b) Lee, J.; Torker, S.; Hoveyda, A. H. Versatile Homoallylic Boronates by Chemo-, SN2′-, Diastereo- and Enantioselective Catalytic Sequence of Cu−H Addition to Vinyl-B(Pin)/Allylic Substitution. *Angew. Chem. Int. Ed.* **2017**, *56*, 821–826.

(10) Mailig, M.; Hazra, A.; Armstrong, M. K.; Lalic, G. Catalytic Anti-Markovnikov Hydroallylation of Terminal and Functionalized Internal Alkynes: Synthesis of Skipped Dienes and Trisubstituted Alkenes. *J. Am. Chem. Soc.* **2017**, *139*, 6969–6977. (b) Xu, G.; Zhao, H.; Fu, B.; Cang, A.; Zhang, G.; Zhang, Q.; Xiong, T.; Zhang, Q. Ligand-Controlled Regiodivergent and Enantioselective Copper-Catalyzed Hydroallylation of Alkynes. *Angew. Chem. Int. Ed.* **2017**, *56*, 13130–13134.

(11) Xu, G.; Fu, B.; Zhao, H.; Li, Y.; Zhang, G.; Wang, Y.; Xiong, T.; Zhang, Q. Enantioselective and Site-Specific Copper-Catalyzed Reductive Allyl–Allyl Cross-Coupling of Allenes. *Chem. Sci.* **2019**, *10*, 1802–1806.

(12) Sommer, H.; Marek, I. Diastereo- and Enantioselective Copper Catalyzed Hydroallylation of Disubstituted Cyclopropenes. *Chem. Sci.* **2018**, *9*, 6503–6508.

(13) (a) Deutsch, C.; Krause, N.; Lipshutz, B. H. CuH-Catalyzed Reactions. *Chem. Rev*. **2008**, *108*, 2916−2927. (b) Lipshutz, B. H. Rediscovering Organocopper Chemistry Through Copper Hydride. It's All About the Ligand. *Synlett* **2009**, 509−524. (c) Jordan, A. J.; Lalic, G.; Sadighi, J. P. Coinage Metal Hydrides: Synthesis, Characterization, and Reactivity. *Chem. Rev*. **2016**, *116*, 8318−8372.

(14) Huang, Y.; Ma, C.; Lee, Y. X.; Huang, R.-Z.; Zhao, Y. Cobalt-Catalyzed Allylation of Heterobicyclic Alkenes: Ligand-Induced Divergent Reactivities. *Angew. Chem. Int. Ed.* **2015**, *54*, 13696–13700.

(15) For an example of Fe-catalyzed HAT hydroallylation of allylacetates, see: Qi, J.; Zheng, J.; Cui, S. Fe(III)-Catalyzed Hydroallylation of Unactivated Alkenes with Morita–Baylis–Hillman Adducts. *Org. Lett.* **2018**, *20*, 1355–1358.

(16) (a) Trost, B. M.; Toste, F. D. Ruthenium-Catalyzed Cycloisomerization of 1,6-Enynes Initiated by C−H Activation. *J. Am. Chem. Soc.* **1999**, *121*, 9728–9729. (b) Brummond, K. M.; Chen, H.; Mitasev, B.; Casarez, A. D. Rhodium(I)-Catalyzed Ene-Allene Carbocyclization Strategy for the Formation of Azepines and Oxepines. *Org. Lett.* **2004** *6*, 2161–2163. (c) Li, Q.; Yu, Z.-X. Conjugated Diene-Assisted Allylic C−H Bond Activation: Cationic Rh(I)-Catalyzed Syntheses of Polysubstituted Tetrahydropyrroles, Tetrahydrofurans, and Cyclopentanes from Ene-2-Dienes, *J. Am. Chem. Soc*. **2010** *132*, 4542–4543. (d) Li, W.; Yuan, W.; Shi, M.; Hernandez, E.; Li, G. Rhodium(I)-Catalyzed Intramolecular Ene Reaction of Vinylidenecyclopropanes and Alkenes for the Formation of Bicyclo[5.1.0]octylenes, *Org. Lett*. **2010** *12*, 64–67. (e) Li, Q.; Yu, Z.-X. Enantioselective Rhodium-Catalyzed Allylic C−H Activation for the Addition to Conjugated Dienes. *Angew. Chem. Int. Ed.* **2011**, *50*, 2144–2147. (f) Lu, B.-L.; Shi, M. Synthesis of Functionalized Polycyclic Compounds: Rhodium(I)-Catalyzed Intramolecular Cycloaddition of Yne and Ene Vinylidenecyclopropanes. *Angew. Chem. Int. Ed.* **2011**, *50*, 12027–12031. (g) Li, Q.; Yu, Z.-X. Density Functional Theory Study of the Mechanism of the Rhodium(I)-Catalyzed Conjugated Diene Assisted Allylic C–H Bond Activation and Addition to Alkenes Using Ene-2-dienes As Substrates, *Organometallics* **2012**, *31*, 5185–519.

(17) (a) Goldfogel, M. J.; Roberts, C. C.; Meek, S. J. Intermolecular Hydroamination of 1,3-Dienes Catalyzed by Bis(Phosphine)Carbodicarbene–Rhodium Complexes. *J. Am. Chem. Soc.* **2014**, *136*, 6227–6230. (b) Roberts, C. C.; Matías, D. M.; Goldfogel, M. J.; Meek, S. J. Lewis Acid Activation of Carbodicarbene Catalysts for Rh-Catalyzed Hydroarylation of Dienes. *J. Am. Chem. Soc.* **2015**, *137*, 6488–6491. (c) Goldfogel, M. J.; Meek, S. J. Diastereoselective Synthesis of Vicinal Tertiary and N-Substituted Quaternary Stereogenic Centers by Catalytic Hydroalkylation of Dienes. *Chem. Sci.* **2016**, *7*, 4079–4084. (d) Goldfogel, M. J.; Roberts, C. C.; Manan, R. S.; Meek, S. J. Diastereoselective Synthesis of γ-Substituted 2-Butenolides via (CDC)-Rh-Catalyzed Intermolecular Hydroalkylation of Dienes with Silyloxyfurans. *Org. Lett.* **2017**, *19*, 90–93.

(18) Marcum, J. S.; Roberts, C. C.; Manan, R. S.; Cervarich, T. N.; Meek, S. J. Chiral Pincer Carbodicarbene Ligands for Enantioselective Rhodium-Catalyzed Hydroarylation of Terminal and Internal 1,3-Dienes with Indoles. *J. Am. Chem. Soc.* **2017**, *139*, 15580–15583.

(19) Lennox, A. J. J.; Lloyd-Jones, G. C. Organotrifluoroborate Hydrolysis: Boronic Acid Release Mechanism and an Acid–Base Paradox in Cross-Coupling. *J. Am. Chem. Soc.* **2012**, *134*, 7431–7441.

(20) For an overview of Rh-catalyzed allylations with alkynes and allenes, see: Koschker, P.; Breit, B. *Acc. Chem. Res.* **2016**, *49*, 1524–1536.

(21) (a) Takahashi, K.; Miyake, A.; Hata, G. Palladium-catalyzed Reactions of 1,3-Dienes with Active Methylene Compounds. IV. Palladium-diphosphine Complex Catalysts. *Bull. Chem. Soc. Jpn.* **1972**, *45*, 1183−1191. (b) Andell, O. S.; Bäckvall, J. E.; Moberg, C. Nickel- and Palladium-Catalyzed Additions of Nucleophiles to Cyclic 1,3-Dienes. *Acta Chem. Scand*. **1986**, *B 40*, 184−189. (c) Mignani, G.; Morel, D.; Colleuille, Y. A Novel Method for the Isoprenylation of β-Dicarbonyl Compounds. *Tet. Lett*. **1985**, *26*, 6337–6340. (d) Leitner, A.; Larsen, J.; Steffens, C.; Hartwig, J. F. Palladium-Catalyzed Addition of Mono- and Dicarbonyl Compounds to Conjugated Dienes. *J. Org. Chem.* **2004**, *69*, 7552–7557. (e) Adamson, N. J.; Wilbur, K. C. E.; Malcolmson, S. J. Enantioselective Intermolecular Pd-Catalyzed Hydroalkylation of Acyclic 1,3-Dienes with Activated Pronucleophiles. *J. Am. Chem. Soc.* **2018**, *140*, 2761–2764.

(22) Ni: (a) Pawlas, J.; Nakao, Y.; Kawatsura, M.; Hartwig, J. F. A General Nickel-Catalyzed Hydroamination of 1,3-Dienes by Alkylamines: Catalyst Selection, Scope, and Mechanism. *J. Am. Chem. Soc.* **2002**, *124* (14), 3669–3679. Pd: (b) Löber, O.; Kawatsura, M.; Hartwig, J. F. Palladium-Catalyzed Hydroamination of 1,3-Dienes: A Colorimetric Assay and Enantioselective Additions. *J. Am. Chem. Soc.* **2001**, *123*, 4366–4367. (c) Adamson, N. J.; Hull, E.; Malcolmson, S. J. Enantioselective Intermolecular Addition of Aliphatic Amines to Acyclic Dienes with a Pd–PHOX Catalyst *J. Am. Chem. Soc.* **2017**, *139*, 7180–7183. (d) Park, S.; Malcolmson, S. J. Development and Mechanistic Investigations of Enantioselective Pd-Catalyzed Intermolecular Hydroaminations of Internal Dienes. *ACS Catalysis* **2018**, *8*, 8468–8476. Rh: (e) Yang, X.-H.; Dong, V. M. Rhodium-Catalyzed Hydrofunctionalization: Enantioselective Coupling of Indolines and 1,3-Dienes *J. Am. Chem. Soc.* **2017**, *139*, 1774–1777.

(23) (a) Liao, L.; Sigman, M. S. Palladium-Catalyzed Hydroarylation of 1,3-Dienes with Boronic Esters via Reductive Formation of π-Allyl Palladium Intermediates under Oxidative Conditions. *J. Am. Chem. Soc.* **2010**, *132* (30), 10209–10211. (b) Podhajsky, S. M.; Iwai, Y.; Cook-Sneathen, A.; Sigman, M. S. Asymmetric palladium-catalyzed hydroarylation of styrenes and dienes *Tetrahedron* **2011**, *67*, 4435–4441. For a recent related enantioselective hydroarylation of alkynes, see: (c) Cruz, F. A.; Zhu, Y.; Tercenio, Q. D.; Shen, Z.; Dong, V. M. Alkyne Hydroheteroarylation: Enantioselective Coupling of Indoles and Alkynes via Rh-Hydride Catalysis. *J. Am. Chem. Soc.* **2017**, *139*, 10641–10644.

(24) (a) Yang, X.-H.; Davison, R. T.; Dong, V. M. Catalytic Hydrothiolation: Regio- and Enantioselective Coupling of Thiols and Dienes. *J. Am. Chem. Soc.* **2018**, *140*, 10443–10446. (b) Yang, X.-H.; Davison, R. T.; Nie, S.-Z.; Cruz, F. A.; McGinnis, T. M.; Dong, V. M.

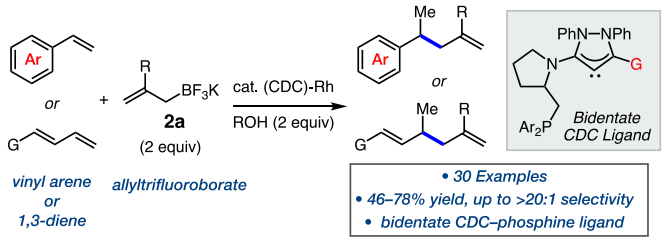
Catalytic Hydrothiolation: Counterion-Controlled Regioselectivity. *J. Am. Chem. Soc.* **2019**, *141*, 3006–3013.

(25) Nie, S.-Z.; Davison, R. T.; Dong, V. M. Enantioselective Coupling of Dienes and Phosphine Oxides. *J. Am. Chem. Soc.* **2018**, *140*, 16450–16454.

(26) Gómez-Gallego, M.; Sierra, M. A. Kinetic Isotope Effects in the Study of Organometallic Reaction Mechanisms. *Chem. Rev.* **2011**, *111*, 4857–4963.

(27) (a) Evans, J.; Johnson, B. F. G.; Lewis, J. Protonation of Cyclo-Octa-1, 5-Diene-and Cyclo-Octa-1, 3, 5-Triene-Cyclopentadienylrhodium (I): Novel Versatility of Metal Co-Ordination. *J. Chem. Soc. D: Chem. Commun.* **1971**, 1252–1253. (b) Henderson, R. A.; Oglieve, K. E. The Formation of Metal Hydrido Complexes via Protonation of Coordinated Ethylene: Relative Rates of Protonation of Coordinated Ethylene and Metal. *J. Chem. Soc. Chem. Commun.* **1991**, 584–586. (c) Henderson, R. A. Protonation of Unsaturated Hydrocarbon Ligands: Regioselectivity, Stereoselectivity, and Product Specificity. *Angew. Chem. Int. Ed. Engl.* **1996**, *35*, 946–967. (d) Öhrström, L.; Strömberg, S.; Glaser, J.; Zetterberg, K. Protonation of π-Alkene–Rhodium (I) Complexes Leads to σ-Alkyl–Rhodium (III)—an NMR Study. *J. Organomet. Chem.* **1998**, *558*, 123–130.

(28) Shekhar, S.; Hartwig, J. F. Distinct Electronic Effects on Reductive Eliminations of Symmetrical and Unsymmetrical Bis-Aryl Platinum Complexes. *J. Am. Chem. Soc.* **2004**, *126*, 13016–13027.


Ar
or
G
R
BF3K
2a
(2 equiv)
cat. (CDC)-Rh
ROH (2 equiv)
Me
R
Ar
or
Me
R
G
PhN—NPh
N
G
Ar2P
Bidentate
CDC Ligand
vinyl arene
or
1,3-diene
allyltrifluoroborate
• 30 Examples
• 46–78% yield, up to >20:1 selectivity
• bidentate CDC–phosphine ligand