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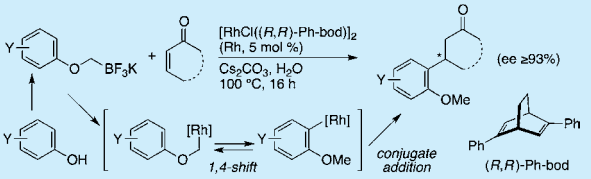
Aryloxymethyltrifluoroborates for Rhodium-Catalyzed Asymmetric Conjugate Arylation. *o*-Methoxyarylation through 1,4-Rhodium Shift

Jialin Ming and Tamio Hayashi*

Division of Chemistry and Biological Chemistry, School of Physical and Mathematical Sciences, Nanyang Technological University, 21 Nanyang Link, Singapore 637371, Singapore

Supporting Information

ABSTRACT: Reaction of potassium aryloxymethyltrifluoroborates **1** with α,β-unsaturated carbonyl compounds **2** in the presence of a chiral diene–rhodium catalyst in H_2O at 100 °C introduced 2-methoxyaryl groups at the β-position of **2** with high enantioselectivity in high yields. The reaction is assumed to proceed through 1,4-Rh shift from aryloxymethyl-Rh intermediate to 2-methoxyaryl-Rh. The high availability of phenol derivatives makes this asymmetric conjugate arylation synthetically useful.



Rhodium-catalyzed asymmetric conjugate arylation of activated alkenes has attracted considerable attention as one of the most convenient and reliable methods of creating benzylic stereocenters with high enantioselectivity.[1] As arylating reagents for the asymmetric arylation, arylboron reagents have been used most frequently because of their easy handling in air and moisture (Scheme 1, eq 1).[2] The arylboron reagents, which possess an aryl carbon–boron bond, are prepared by the borylation of Ar–M (M = Li, Mg) reagents in most cases. Borylation of Ar–X (X = halides, triflate) and Ar–H by transition-metal-catalyzed reaction with diboron reagents is another preparation method which has been developed recently.[3]

On the other hand, Molander reported synthesis of alkoxymethyltrifluoroborates ($ROCH_2BF_3K$) from alcohols (ROH) and their use as alkoxymethyl nucleophiles in the palladium-catalyzed cross-coupling reactions[4,5] (Scheme 1, eq 2). Herein, we report that the reaction of aryloxymethyltrifluoroborates ($ArOCH_2BF_3K$) with α,β-unsaturated carbonyl compounds in the presence of a chiral diene–rhodium catalyst introduces *o*-methoxyaryl groups at the β-position in high yields with high enantioselectivity, where the reaction proceeds through the 1,4-shift of rhodium[6,7] from aryloxymethyl to *o*-methoxyaryl intermediates (Scheme 1, eq 3). Considering the very wide availability of substituted phenols and their easy conversion into aryloxymethyltrifluoroborates,[4,5] this 1,4-shift/arylation sequential reaction is of great advantage over the reaction of *o*-methoxyarylboron reagents. The 1,4-Rh shift from alkyl-Rh to aryl-Rh intermediates[6] has been reported to be involved as a key step in the catalytic cycle of several types of rhodium-catalyzed reactions, which have been developed since Miura's report in 2000.[6a] As a reaction related to the present study, there has been a report where the Rh shift between aryloxymethyl and *o*-methoxyaryl is proposed to explain a methoxy-directed aryl-to-aryl 1,3-Rh migration.[8]

In the first set of experiments, benzalacetone **2a** was allowed to react with phenoxymethyltrifluoroborate **1a** (1.2 equiv to **2a**) in the presence of 5 mol % of a rhodium catalyst coordinated with (*R*,*R*)-Ph-bod,[9] which is one of the most commonly used chiral diene ligands.[10] The reaction with Cs_2CO_3 (2.0 equiv) as a base in dioxane/H_2O (10:1) at 60 °C for 16 h, which is one of the standard conditions for rhodium-catalyzed asymmetric conjugate arylation,[1] did not give any addition products (Table 1, entry 1). This is as expected because the rhodium-catalyzed conjugate addition of organoboron reagents is known to work well for the introduction of aryl and alkenyl groups but not for that of alkyl groups.[1] On heating the reaction to 100 °C, formation of addition product **3aa**, where the 2-methoxyphenyl

Scheme 1. Rh-Catalyzed Conjugate Arylation, Aryloxymethyl Intermediates, and 1,4-Rh Shift

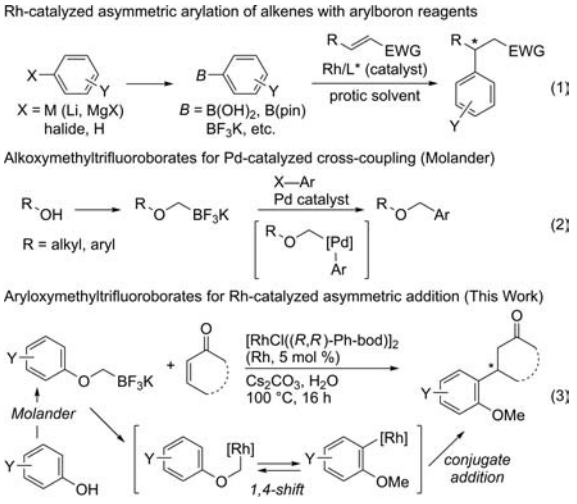


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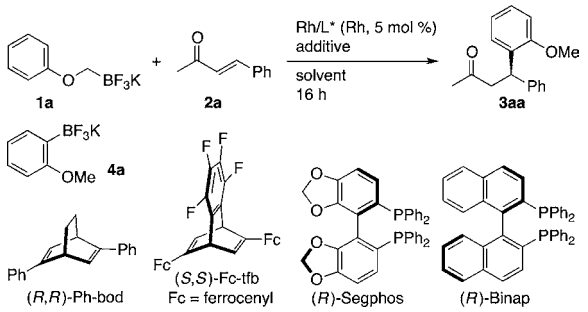
Table 1. Rhodium-Catalyzed Asymmetric Arylation of Benzalacetone 2a with Phenoxymethylborate 1a[a]

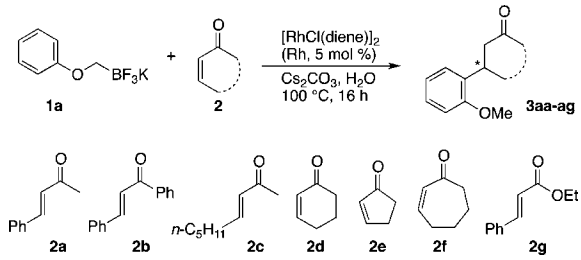


entry	ligand on Rh	additive (equiv)	solvent (mL)	temp (°C)	3aa yield[b] (%)	3aa % ee[c]
1	(*R*,*R*)-Ph-bod[d]	Cs_2CO_3 (2)	dioxane/H_2O (1.0:0.1)	60	0	
2	(*R*,*R*)-Ph-bod[d]	Cs_2CO_3 (2)	dioxane/H_2O (1.0:0.1)	80	3	
3	(*R*,*R*)-Ph-bod[d]	Cs_2CO_3 (2)	dioxane/H_2O (1.0:0.1)	100	19	
4	(*R*,*R*)-Ph-bod[d]	Cs_2CO_3 (2)	dioxane/H_2O (0.5:0.5)	100	57	98
5	(*R*,*R*)-Ph-bod[d]	Cs_2CO_3 (2)	toluene/H_2O (0.5:0.5)	100	70	98
6	(*R*,*R*)-Ph-bod[d]	Cs_2CO_3 (2)	H_2O (1.1)	100	86	98
7[e]	(*R*,*R*)-Ph-bod[d]	Cs_2CO_3 (4)	H_2O (1.1)	100	96	98
8[f]	(*R*,*R*)-Ph-bod[d]	Cs_2CO_3 (2)	H_2O (1.1)	100	91	98
9	(*R*,*R*)-Ph-bod[d]	K_3PO_4 (2)	H_2O (1.1)	100	76	98
10	(*R*,*R*)-Ph-bod[d]	KOH (2)	H_2O (1.1)	100	<3	
11	(*S*,*S*)-Fc-tfb[g]	Cs_2CO_3 (2)	H_2O (1.1)	100	42	>99.5
12	(*R*)-Binap[h]	Cs_2CO_3 (2)	H_2O (1.1)	100	39	99
13	(*R*)-Segphos[i]	Cs_2CO_3 (2)	H_2O (1.1)	100	<3	

[a]Reaction conditions: **1a** (0.24 mmol), **2a** (0.20 mmol), and Rh catalyst (5 mol % Rh), for 16 h. [b]Isolated yield. [c]The % ee was determined by HPLC on a chiral stationary phase column. [d]$[RhCl((R,R)\text{-Ph-bod})]_2$. [e]With **1a** (0.40 mmol). [f]Reaction with **4a** (0.24 mmol) instead of **1a**. [g]$[RhCl((S,S)\text{-Fc-tfb})]_2$. [h]$[RhCl(coe)_2]_2$/(*R*)-Binap. [i]$[RhCl(coe)_2]_2$/(*R*)-Segphos.

group was introduced at the β-position instead of the phenoxymethyl group, was observed albeit in a low yield (19%) (Table 1, entry 3). The yield of **3aa** was found to be higher with a higher ratio of water (Table 1, entries 4 and 5), and the reaction in pure water[11] gave the highest yield (86%) of **3aa**, which is an *R* isomer of 98% ee (Table 1, entry 6). A larger amount (2.0 equiv of **2a**) of boron reagent **1a** increased the yield of **3aa** to 96% (Table 1, entry 7). The use of 2-methoxyphenyltrifluoroborate **4a** in place of **1a** gave essentially the same result (91% yield, 98% ee) (Table 1, entry 8), which may well suggest that the reaction proceeds through a 2-methoxyphenyl-Rh intermediate (vide infra). The yield of **3aa** was slightly lower with K_3PO_4 as a base (Table 1, entry 9), and KOH is not an appropriate base for the present reaction (Table 1, entry 10). Another choice of chiral diene ligand is Fc-tfb, whose enantioselectivity is higher than that of Ph-bod in most of the rhodium-catalyzed asymmetric arylation reactions.[12] Although Fc-tfb ligand is not better than Ph-bod for the addition to enone **2a** due to the lower yield (Table 1, entry 11), Fc-tfb ligand shows higher performance for some other enone substrates (see Table 2). The yields are low with bisphosphine ligands, binap, and segphos (Table 1, entries 12 and 13).

Table 2. Rhodium-Catalyzed Asymmetric Arylation of Enones 2 with Phenoxymethylborate 1a[a]



entry	2	diene ligand	3 (yield %)[b]	ee %[c] (conf)
1	**2a**	(*R*,*R*)-Ph-bod	**3aa** (86)	98 (*R*)
2	**2b**	(*R*,*R*)-Ph-bod	**3ab** (94)	>99.5 (*R*)
3	**2c**	(*R*,*R*)-Ph-bod	**3ac** (84)	97 (*S*)
4	**2d**	(*R*,*R*)-Ph-bod	**3ad** (67)	87 (*R*)
5[d]	**2d**	(*R*,*R*)-Ph-bod	**3ad** (82)	88 (*R*)
6[d]	**2d**	(*S*,*S*)-Fc-tfb	**3ad** (77)	94 (*R*)
7	**2e**	(*R*,*R*)-Ph-bod	**3ae** (76)	96 (*R*)
8	**2f**	(*R*,*R*)-Ph-bod	**3af** (75)	88 (*R*)
9[d]	**2f**	(*S*,*S*)-Fc-tfb	**3af** (81)	93 (*R*)
10[d]	**2g**	(*R*,*R*)-Ph-bod	**3ag** (87)	97 (*R*)

[a]Reaction conditions: **1a** (0.24 mmol), enone **2** (0.20 mmol), Cs_2CO_3 (0.40 mmol), $[RhCl((R,R)\text{-Ph-bod})]_2$ (5 mol % of Rh), H_2O (1.1 mL) at 100 °C for 16 h. [b]Isolated yield. [c]The % ee was determined by HPLC on chiral stationary phase columns. The absolute configuration of **3ad** is known, and others are estimated by stereochemical similarity to those reported for asymmetric arylation with Rh/(*R*,*R*)-Ph-bod catalyst. [d]With **1a** (0.40 mmol) and Cs_2CO_3 (0.80 mmol).

The results for the 1,4-shift/arylation reaction of **1a** with several other α,β-unsaturated carbonyl compounds are summarized in Table 2. The yields and % ee's of the products are high for linear enones, chalcone **2b**, and 3-nonen-2-one (**2c**) under the conditions using 1.2 equiv of **1a** in the presence of $[RhCl((R,R)\text{-Ph-bod})]_2$ (Rh, 5 mol %) catalyst (Table 2, entries 2 and 3). For 2-cyclohexenone (**2d**), the yield and % ee were not satisfactory (67% yield, 87% ee) under the same conditions (Table 2, entry 4). The yield was improved from 67% to 82% by use of 2.0 equiv of boron reagent **1a** (Table 2, entry 5), and % ee was increased to 94% ee by changing the diene ligand to (*S*,*S*)-Fc-tfb (Table 2, entry 6). The reaction of 2-cycloheptenone (**2f**) was also improved by use of (*S*,*S*)-Fc-tfb ligand and an excess amount of **1a** (Table 2, entries 8 and 9). α,β-Unsaturated ester **2g** is also a suitable substrate for the 1,4-shift/arylation reaction (Table 2, entry 10).

Aryloxymethylborates bearing substituents on the phenyl group, which were prepared from the corresponding phenol derivatives according to the Molander's procedures,[4] were subjected to the present 1,4-shift/arylation reaction (Table 3). Those substituted with Me (**1b**), MeO (**1c**), F (**1d**), Cl (**1e**), Br (**1f**), CF_3 (**1g**), and COOEt (**1h**) at the para position gave high yields of the arylation products **5** with high ee in the reaction with **2a** and/or **2b** in the presence of $[RhCl((R,R)\text{-Ph-bod})]_2$ (Rh, 5 mol %) catalyst (Table 3, entries 1−8). The introduced aromatic groups in **5** are all substituted at the 5-position in addition to the

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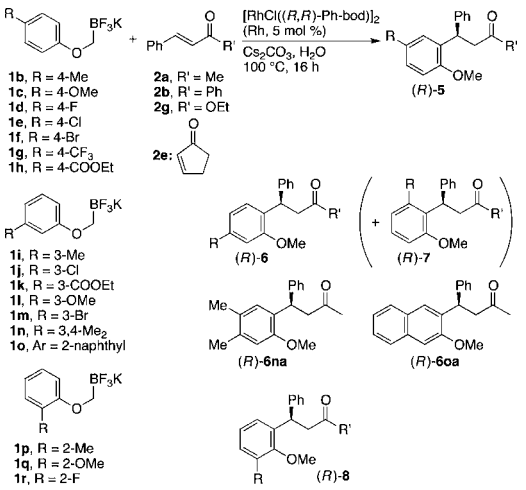
Table 3. Rhodium-Catalyzed Asymmetric Arylation of Enones 2 with Substituted Aryloxymethylborates 1[a]



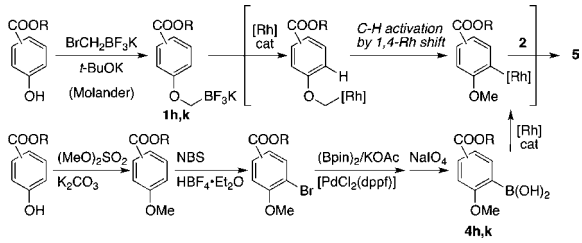
entry	1	2	regioselectivity[b]	yield[c] (%)	ee[d] (%)
1	**1b**	**2a**		**5ba**, 90	99
2	**1c**	**2a**		**5ca**, 92	98
3	**1d**	**2b**		**5db**, 83	>99.5
4	**1e**	**2b**		**5eb**, 86	>99.5
5[e]	**1f**	**2a**		**5fa**, 85	98
6	**1f**	**2b**		**5fb**, 84	99
7	**1g**	**2b**		**5gb**, 90	99
8	**1h**	**2b**		**5hb**, 87	>99.5
9	**1i**	**2a**	**6**/**7** = >50:1	**6ia**, 89	99
10	**1i**	**2b**	**6**/**7** = >50:1	**6ib**, 97	99
11[e]	**1j**	**2b**	**6**/**7** = >50:1	**6jb**, 91	99
12[e]	**1k**	**2b**	**6**/**7** = >50:1	**6kb**, 87	99
13	**1l**	**2a**	**6**/**7** = 7:1	**6la**, 92[f]	99
14	**1l**	**2b**	**6**/**7** = 12:1	**6lb**, 94[f]	>99.5
15	**1l**	**2e**	**6**/**7** = 11:1	**6le**, 77[f]	96
16	**1l**	**2g**	**6**/**7** = 9:1	**6lg**, 92[f]	98
17[e]	**1m**	**2b**	**6**/**7** = 6:1	**6mb**, 86[f]	>99.5
18	**1n**	**2a**	**6**/**7** = >50:1	**6na**, 91	99
19	**1o**	**2a**	**6**/**7** = >50:1	**6oa**, 80	98
20[e]	**1p**	**2a**		**8pa**, 72	99
21[e]	**1q**	**2a**		**8qa**, 78	97
22[e]	**1r**	**2a**		**8ra**, 74	97

[a]Reaction conditions: **1** (0.24 mmol), enone **2** (0.20 mmol), Cs_2CO_3 (0.40 mmol), $[RhCl((R,R)\text{-Ph-bod})]_2$ (5 mol % of Rh), H_2O (1.1 mL) at 100 °C for 16 h. [b]Determined by ^1H NMR. [c]Isolated yield. [d]The ee was determined by HPLC on chiral columns. The absolute configuration of **5fb** was determined to be *R* by X-ray analysis (CCDC 1500570), and others are estimated by stereochemical similarity to those reported for asymmetric arylation with Rh/(*R*,*R*)-Ph-bod catalyst. [e]With **1** (0.40 mmol) and Cs_2CO_3 (0.80 mmol). [f]Yield of a mixture of **6** and **7**.

MeO group at the 2-position, as expected by the 1,4-Rh shift mechanism. In the reaction of aryloxymethylborates with substituents at the meta-position, the regioselectivity at the 1,4-Rh shift in giving 2,4-disubstituted isomer **6** or 2,6-disubstituted isomer **7** is an interesting subject of study. With Me (**1i**), Cl (**1j**), and COOEt (**1k**) at the 3-position, the regioselectivity is very high to give the less hindered isomers **6** exclusively (Table 3, entries 9−12). With OMe (**1l**) and Br (**1m**) as 3-substituents, the regiochemistry is not perfect, with the **6**/**7** ratio ranging between 12:1 and 6:1 (Table 3, entries 13−17). It is notable that the selectivity is not strongly dependent on the enone/enoate substrates. The regioselective 1,4-shift leading to less hindered isomers **6na** and **6oa** was also observed in the reaction of aryloxymethylborates where the aryl groups are 3,4-dimethylphenyl (**1n**) and 2-naphthyl (**1o**) (Table 3, entries 18 and 19). The 1,4-shift/arylation reaction is also applicable to the ortho-substituted borates **1p**, **1q**, and **1r**, which gave the corresponding arylation products **8** although the yields are somewhat lower (Table 3, entries 20−22).

The 1,4-shift/arylation products **5**−**8** shown in Table 3 are expected to be also obtainable by use of the corresponding *o*-methoxyarylboronic acids (see Table 1, entry 8), but the synthesis of aryloxymethylborates from phenol derivatives is generally much more straightforward than that of the *o*-methoxyarylboronic acids. As an example, the reported synthetic scheme for ester-substituted 2-methoxyphenylboronic acids **4h**,**k**[13] is shown in Scheme 2, where ester-substituted phenols

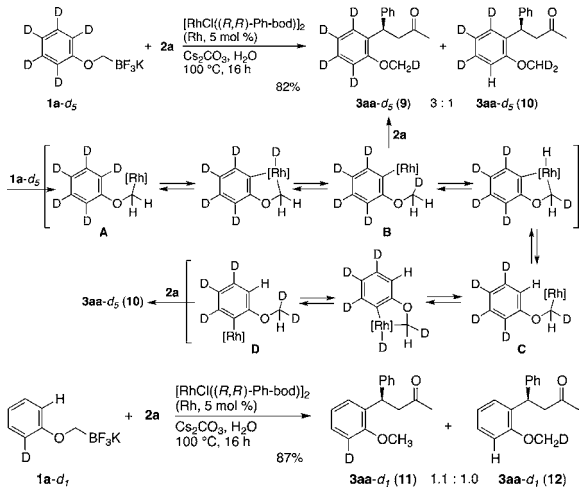
Scheme 2. Comparison of Synthesis and Reaction of Aryloxymethylborates 1 with *o*-Methoxyphenylboronic Acids 4



were converted into the boronic acids by multiple step reactions including ortho-bromination and palladium-catalyzed borylation. On the contrary, the aryloxymethylborates **1h**,**k** are prepared in one step from the phenols by Molander's method.[4] It should be noted that the present rhodium catalysis can skip the ortho C−H functionalization steps required for the synthesis of *o*-methoxyarylboron reagents.

Deuterium-labeling studies provided us with some information on the mechanism of 1,4-Rh shift from phenoxymethyl carbon to 2-methoxyphenyl carbon (Scheme 3). The product **3aa**-d_5 formed by the reaction of pentadeuteriophenoxymethylborate **1a**-d_5 with benzalacetone **2a** was found to be a mixture of

Scheme 3. Deuterium-Labeling Studies on the 1,4-Rh Shift during the Rhodium-Catalyzed Hydroarylation



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deuterium regioisomers **3aa**-d_5 **9** and **3aa**-d_5 **10** in a ratio of 3:1. The reaction pathway to produce isomer **9**, which is substituted with an OCH_2D group at the 2-position and with D_4 at other positions, is simple. Transmetalation of the phenoxymethyl group from boron to rhodium generates alkyl-Rh intermediate **A**, which is not reactive toward the addition to enone[14] but undergoes the 1,4-Rh shift by way of a Rh(III) species[15] to form a 2-methoxyphenyl-Rh intermediate **B**. Addition of aryl-Rh **B** to enone **2a** produces isomer **9**. The reversibility of 1,4-Rh shift between sp^3 carbon and sp^2 carbon is demonstrated by the formation of isomer **10**, where the methoxy group at 2-position is $OCHD_2$ and H is at 3-position. The 1,4-shift from 2-methoxyphenyl-Rh intermediate **B** goes back to **A** or generates a new alkyl-Rh **C** where H and D are exchanged. The 1,4-Rh shift to the other side of ortho carbon forms aryl-Rh intermediate **D**, which finally leads to isomer **10** by addition to enone **2a**.

Deuterium kinetic isotope effects (KIE) were studied for intramolecular competition[16,17] in the reaction of 2-deuteriophenoxymethylborate **1a**-d_1. In the product **3aa**-d_1, deuterium was incorporated at the aromatic carbon (**11**) and at the methoxy carbon (**12**) in a ratio of 1.1:1.0. This small KIE (k_H/k_D = 1.1) may suggest that the C−H bond breaking is not a turnover-limiting step in the present reaction.

■ ASSOCIATED CONTENT

Supporting Information

Experimental procedures, compound characterization data, and crystallographic data (CIF). The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.orglett.6b03347.

X-ray data for **5fb** (CIF)
Experimental procedures, compound characterization data, and crystallographic data (PDF)

■ AUTHOR INFORMATION

Corresponding Author

*E-mail: hayashi@ntu.edu.sg.

ORCID

Tamio Hayashi: 0000-0001-9187-3664

Notes

The authors declare no competing financial interest.

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■ REFERENCES

(1) For pertinent reviews, see: (a) Heravi, M. M.; Dehghani, M.; Zadsirjan, V. *Tetrahedron: Asymmetry* **2016**, *27*, 513. (b) Tian, P.; Dong, H.-Q.; Lin, G.-Q. *ACS Catal.* **2012**, *2*, 95. (c) Berthon, G.; Hayashi, T. In *Catalytic Asymmetric Conjugate Reactions*; Córdova, A., Ed.; Wiley-VCH: Weinheim, 2010; Chapter 1, p 1.

(2) For pertinent books on boronic acids and related organoboron reagents, see: (a) Hall, D. G., Ed.; *Boronic Acids*; Wiley-VCH: Weinheim, 2005. (b) Hall, D. G., Ed.; *Boronic Acids*, 2nd ed.; Wiley-VCH: Weinheim, 2011.

(3) Hall, D. G. In *Boronic Acids*, 2nd ed.; Hall, D. G., Ed.; Wiley-VCH: Weinheim, 2011; Chapter 1, p 1. (b) Ishiyama, T.; Miyaura, N. In *Boronic Acids*, 2nd ed.; Hall, D. G., Ed.; Wiley-VCH: Weinheim, 2011; Chapter 2, p 135.

(4) (a) Molander, G. A.; Canturk, B. *Org. Lett.* **2008**, *10*, 2135. (b) Molander, G. A.; Ham, J. *Org. Lett.* **2006**, *8*, 2031. (c) Molander, G. A.; Beaumard, F. *Org. Lett.* **2011**, *13*, 3948. (d) Molander, G. A.; Wisniewski, S. R. *J. Am. Chem. Soc.* **2012**, *134*, 16856. See also: (e) Miyazawa, K.; Yasu, Y.; Koike, T.; Akita, M. *Chem. Commun.* **2013**, *49*, 7249.

(5) For reviews on organotrifluoroborates, see: (a) Molander, G. A. *J. Org. Chem.* **2015**, *80*, 7837. (b) Darses, S.; Genet, J.-P. *Chem. Rev.* **2008**, *108*, 288. (c) Stefani, H.; Cella, R.; Vieira, A. S. *Tetrahedron* **2007**, *63*, 3623. (d) Molander, G. A.; Ellis, N. *Acc. Chem. Res.* **2007**, *40*, 275.

(6) For the 1,4-rhodium shift from alkylrhodium to arylrhodium intermediates, see: (a) Oguma, K.; Miura, M.; Satoh, T.; Nomura, M. *J. Am. Chem. Soc.* **2000**, *122*, 10464. (b) Matsuda, T.; Shigeno, M.; Murakami, M. *J. Am. Chem. Soc.* **2007**, *129*, 12086. (c) Menard, F.; Lautens, M. *Angew. Chem., Int. Ed.* **2008**, *47*, 2085. (d) Panteleev, J.; Menard, F.; Lautens, M. *Adv. Synth. Catal.* **2008**, *350*, 2893. (e) Seiser, T.; Roth, O. A.; Cramer, N. *Angew. Chem., Int. Ed.* **2009**, *48*, 6320. (f) Shigeno, M.; Yamamoto, T.; Murakami, M. *Chem. - Eur. J.* **2009**, *15*, 12929. (g) Seiser, T.; Cramer, N. *Chem. - Eur. J.* **2010**, *16*, 3383. (h) Seiser, T.; Cramer, N. *Angew. Chem., Int. Ed.* **2010**, *49*, 10163. (i) Matsuda, T.; Suda, Y.; Takahashi, A. *Chem. Commun.* **2012**, *48*, 2988. (j) Prakash, P.; Jijy, E.; Shimi, M.; Aparna, P. S.; Suresh, E.; Radhakrishnan, K. V. *RSC Adv.* **2013**, *3*, 19933. (k) Yu, H.; Wang, C.; Yang, Y.; Dang, Z.-M. *Chem. - Eur. J.* **2014**, *20*, 3839. (l) Shintani, R.; Iino, R.; Nozaki, K. *J. Am. Chem. Soc.* **2014**, *136*, 7849. (m) Kantchev, E. A. B.; Pangestu, S. R.; Zhou, F.; Sullivan, M. B.; Su, H.-B. *Chem. - Eur. J.* **2014**, *20*, 15625. (n) Sawano, T.; Hashizume, M.; Nishimoto, S.; Ou, K.; Nishimura, T. *Org. Lett.* **2015**, *17*, 2630. (o) Matsuda, T.; Yasuoka, S.; Watanuki, S.; Fukuhara, K. *Synlett* **2015**, *26*, 1233.

(7) For reviews dealing with 1,4-metal shift, see: (a) Croisant, M. F.; van Hoveln, R.; Schomaker, J. M. *Eur. J. Org. Chem.* **2015**, *2015*, 5897. (b) Shi, F.; Larock, R. C. *Top. Curr. Chem.* **2009**, *292*, 123. (c) Ma, S.; Gu, Z. *Angew. Chem., Int. Ed.* **2005**, *44*, 7512.

(8) Zhang, J.; Liu, J.-F.; Ugrinov, A.; Pillai, A. F. X.; Sun, Z.-M.; Zhao, P. *J. Am. Chem. Soc.* **2013**, *135*, 17270.

(9) (a) Otomaru, Y.; Okamoto, K.; Shintani, R.; Hayashi, T. *J. Org. Chem.* **2005**, *70*, 2503. (b) Abele, S.; Inauen, R.; Spielvogel, D.; Moessner, C. *J. Org. Chem.* **2012**, *77*, 4765.

(10) For reviews on chiral diene ligands: see, (a) Defieber, C.; Grützmacher, H.; Carreira, E. M. *Angew. Chem., Int. Ed.* **2008**, *47*, 4482. (b) Shintani, R.; Hayashi, T. *Aldrichimica Acta* **2009**, *42*, 31. (c) Feng, C. G.; Xu, M.-H.; Lin, G.-Q. *Synlett* **2011**, *2011*, 1345. (d) Feng, X.; Du, H. *Asian J. Org. Chem.* **2012**, *1*, 204.

(11) For examples of the rhodium-catalyzed reaction of arylboron reagents in water, see: (a) Feng, C.-G.; Wang, Z.-Q.; Shao, C.; Xu, M.-H.; Lin, G.-Q. *Org. Lett.* **2008**, *10*, 4101. (b) Kurahashi, T.; Shinokubo, H.; Osuka, A. *Angew. Chem., Int. Ed.* **2006**, *45*, 6336. (c) Lautens, M.; Mancuso, J. *J. Org. Chem.* **2004**, *69*, 3478.

(12) (a) Nishimura, T.; Kumamoto, H.; Nagaosa, M.; Hayashi, T. *Chem. Commun.* **2009**, 5713. (b) Lim, K. M.-H.; Hayashi, T. *J. Am. Chem. Soc.* **2015**, *137*, 3201. (c) Huang, Y.; Hayashi, T. *J. Am. Chem. Soc.* **2015**, *137*, 7556 and references cited therein.

(13) (a) Ogura, T.; Usuki, T. *Tetrahedron* **2013**, *69*, 2807. (b) Kikuchi, H.; Matsuo, Y.; Katou, Y.; Kubohara, Y.; Oshima, Y. *Tetrahedron* **2012**, *68*, 8884. (c) Bugge, S.; Buene, A. F.; Jurisch-Yaksi, N.; Moen, I. U.; Skjønsfjell, E. M.; Sundby, E.; Hoff, B. H. *Eur. J. Med. Chem.* **2016**, *107*, 255.

(14) It is well documented that rhodium-catalyzed asymmetric conjugate addition is very efficient for arylation and alkenylation but not for alkylation (ref 1).

(15) For computational studies, see: Sasaki, K.; Nishimura, T.; Shintani, R.; Kantchev, E. A. B.; Hayashi, T. *Chem. Sci.* **2012**, *3*, 1278. See also ref 6m.

(16) For a review on deuterium kinetic isotope effects at C−H functionalization, see: Simmons, E. M.; Hartwig, J. F. *Angew. Chem., Int. Ed.* **2012**, *51*, 3066.

(17) For recent reports on the intramolecular KIE studies, see: (a) Boobalan, R.; Gandeepan, P.; Cheng, C.-H. *Org. Lett.* **2016**, *18*, 3314. (b) Sun, Y.-H.; Sun, T.-Y.; Wu, Y.-D.; Zhang, X.; Rao, Y. *Chem. Sci.* **2016**, *7*, 2229. (c) Wang, L.; Pan, L.; Huang, Y.; Chen, Q.; He, M. *Eur. J. Org. Chem.* **2016**, *2016*, 3113.

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