JACS
JOURNAL OF THE AMERICAN CHEMICAL SOCIETY
Communication
pubs.acs.org/JACS

Asymmetric Synthesis of Triarylmethanes by Rhodium-Catalyzed Enantioselective Arylation of Diarylmethylamines with Arylboroxines

Yinhua Huang[†] and Tamio Hayashi*[,†,‡]

[†]Department of Chemistry, National University of Singapore, 3 Science Drive 3, Singapore 117543, Singapore
[‡]Institute of Materials Research and Engineering, A*STAR, 3 Research Link, Singapore 117602, Singapore

Supporting Information

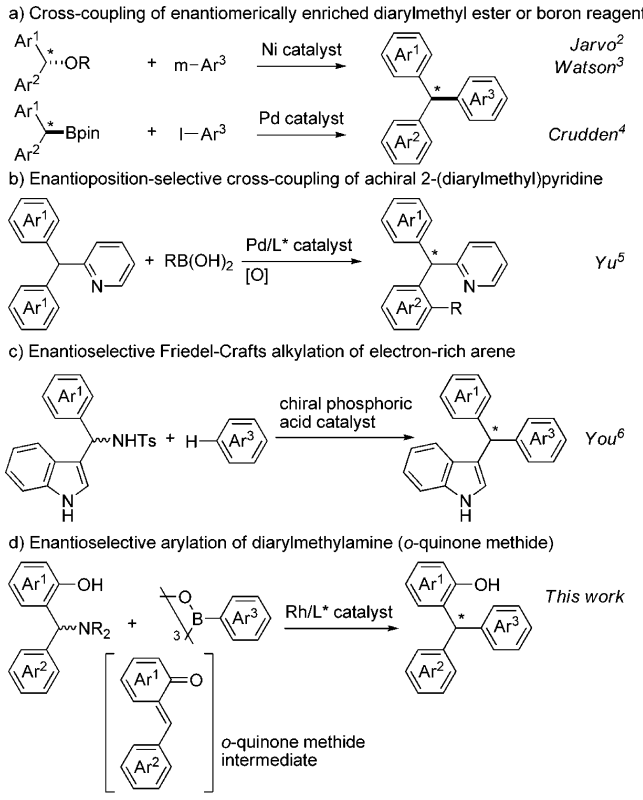
ABSTRACT: The reaction of racemic diarylmethylamines, ($Ar^1Ar^2CHNR_2$), where Ar^1 is substituted with a 2-hydroxy group, with arylboroxines $(Ar^3BO)_3$ in the presence of a chiral diene-rhodium catalyst gave high yields of chiral triarylmethanes ($Ar^1Ar^2CH*Ar^3$) with high enantioselectivity (up to 97% ee). The reaction is assumed to proceed through *o*-quinone methide intermediates which undergo Rh-catalyzed asymmetric 1,4-addition of the arylboron reagents.

Triarylmethanes ($Ar^1Ar^2Ar^3CH$) are known to be an important class of compounds because of their high utility in medicinal chemistry and materials science as well as in organic synthesis.[1] The enantiomerically enriched triarylmethanes have been synthesized by a few methods including asymmetric catalysis, which are summarized in Scheme 1. They are: (a) stereospecific Ni- or Pd-catalyzed cross-coupling of enantiomerically enriched diarylmethyl esters[2,3] or boron reagents;[4] (b) enantioposition-selective oxidative cross-coupling of 2-(diarylmethyl)pyridine catalyzed by a chiral Pd catalyst;[5] and (c) asymmetric Friedel−Crafts alkylation of electron-rich arenes catalyzed by a chiral phosphoric acid.[6] Here we report a new type of asymmetric synthesis of triarylmethanes which is realized by Rh-catalyzed enantioselective substitution of diarylmethylamines with arylboron reagents (Scheme 1d).

On the other hand, it has been well recognized that the rhodium-catalyzed asymmetric arylation of olefins with arylboron reagents is one of the most convenient and reliable methods of creating benzylic stereocenters with high enantioselectivity.[7] The olefinic substrates successfully applied for the asymmetric arylation are mainly electron-deficient olefins, typically those activated by carbonyl groups such as α,β-unsaturated ketones.[8] We envisioned that *o*-quinone methide,[9] which is classified as an α,β-unsaturated ketone, could be an appropriate substrate for the catalytic asymmetric synthesis of chiral triarylmethanes.

At initiating our studies, the reaction of isolated quinone methide **1a**, which is obtained according to a reported procedure,[10] was examined for its reactivity under some of the standard conditions used for α,β-unsaturated ketones.[7] Thus, **1a** was allowed to react with phenylboroxine (**2a**) in the presence of $[RhCl(cod)]_2$ (5 mol % of Rh) and KOH (40 mol %) in dioxane/H_2O (10/1) at 40 °C.[11] All the quinone methide **1a** was consumed within 15 h to give 82% yield of triarylmethane **3aa** together with 18% of a cyclic phenylboronate **4a** (entry 1 in Table 1). Use of $[RhCl((R)\text{-binap})]_2$[12] as a catalyst under the same conditions gave a lower yield (61%) of triarylmethane **3aa** with 79% ee (entry 2). These results demonstrate that the quinone methide can be an appropriate substrate for the rhodium-catalyzed asymmetric arylation forming chiral triarylmethanes, but the low availability of isolable quinone methides is a serious drawback in studying the present asymmetric reactions. Based on the report by Schaus that the ethyl ether **5a** is a good precursor to generate quinone methide in situ for their asymmetric addition of boronates catalyzed by a chiral binaphthol,[13,14] we examined **5a** for the rhodium-catalyzed asymmetric arylation. It turned out that the yield of triarylmethane is low under the basic conditions with both cod and binap-rhodium catalysts, cyclic boronate **4a** being the major

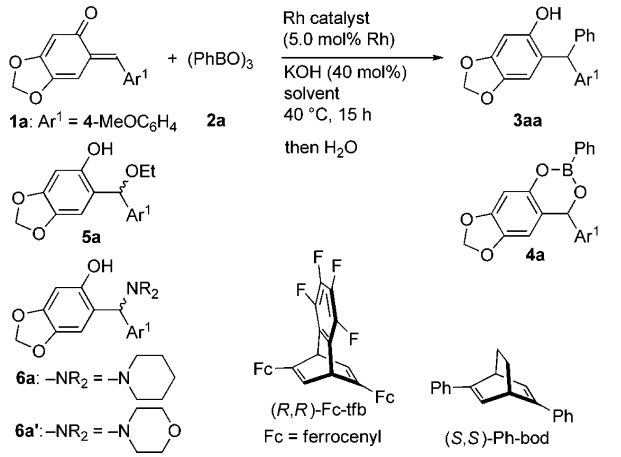
Scheme 1. Synthesis of Enantiomerically Enriched Triarylmethanes



Received: March 30, 2015
Published: June 2, 2015

DOI: 10.1021/jacs.5b03277
J. Am. Chem. Soc. 2015, 137, 7556−7559

Table 1. Rhodium-Catalyzed Asymmetric Arylation of Quinone Methide 1a and Its Precursors 5a and 6a with Phenylboroxine (2a)



entry	subst	ligand on Rh	solvent[b]	yield (%)[c] 3aa	yield (%)[c] 4a	% ee[d] 3aa
1	**1a**	cod[e]	dioxane/H_2O	82	18	—
2	**1a**	(*S*)-binap[f]	dioxane/H_2O	61	39	79
3	**5a**	cod[e]	dioxane/H_2O	18	82	—
4	**5a**	(*S*)-binap[f]	dioxane/H_2O	16	84	51
5	**4a**	cod[e]	dioxane/H_2O	0	100	—
6	**6a**	cod[e]	dioxane/H_2O	22[g]	18	—
7	**6a**	(*S*)-binap[f]	dioxane/H_2O	15[g]	12	76
8	**6a**	cod[e]	dioxane	81[g]	12	—
9	**6a**	(*S*)-binap[f]	dioxane	55 (55)[g]	26	72
10	**6a**	(*R*,*R*)-Fc-tfb[h]	dioxane	87 (85)	13	95
11	**6a**	(*S*,*S*)-Ph-bod[i]	dioxane	78 (72)	16	81
12	**6a**	(*S*,*S*)-Ph-tfb[i]	dioxane	78 (76)	17	64
13	**6a**	(*S*)-segphos[j]	dioxane	59 (56)	23	96
14	**6a**	(*R*,*R*)-Fc-tfb[h]	THF	70 (66)	13	94
15	**6a**	(*R*,*R*)-Fc-tfb[h]	toluene	64 (62)	22	92
16	**6a**	(*R*,*R*)-Fc-tfb[h]	dichloroethane	59 (57)	15	92
17	**6a′**	(*R*,*R*)-Fc-tfb[h]	dioxane	79 (78)	21	94

[a]Reaction conditions: **1a**, **5a**, or **6a** (0.12 mmol), $(PhBO)_3$ (**2a**) (0.12 mmol (0.36 mmol of B)), Rh catalyst (5 mol % of Rh), and KOH (0.048 mmol). [b]Solvent: dioxane/H_2O (1.0/0.1 mL), dioxane, THF, toluene, dichloroethane (1.0 mL). [c]The yields are obtained by ^1H NMR analysis of the crude reaction mixture. Isolated yields in parentheses. [d]The % ee was determined by HPLC on a chiral stationary phase column. [e]$[RhCl(cod)]_2$. [f]$[RhCl((R)\text{-binap})]_2$. [g]**6a** was recovered in 60%, 73%, 7%, and 19% in entries 6, 7, 8, and 9, respectively. [h]$[RhCl((R,R)\text{-Fc-tfb})]_2$. [i]$[RhCl(coe)_2]_2$/(*S*,*S*)-Ph-bod. [j]$[RhCl(coe)_2]_2$/(*S*)-segphos.

product (entries 3–4). It is noted that cyclic boronate **4a** is too stable to generate the quinone methide under the reaction conditions[15] (entry 5).

Our attention was turned to diarylmethylamines as precursors of quinone methide,[9] which are readily prepared from phenol derivatives, aromatic aldehydes, and secondary amines,[16] and are isolated pure without difficulty due to their high stability compared with the diarylmethyl ether analogs such as **5a**. The diarylmethylamine **6a**,[17] where the amino group is piperidino, was subjected to the rhodium-catalyzed arylation. Although the conversion of **6a** is not high in the dioxane/H_2O mixed solvent, the triarylmethane **3aa** was formed in 22% and 15% yields with the Rh-cod and Rh-binap catalysts, respectively (entries 6 and 7). Screening of the reaction solvents revealed that the reaction in dioxane without H_2O greatly improves the yield of triarylmethane. Thus, the yields of **3aa** were increased to 81% and 55% with the Rh-cod and Rh-binap catalysts, respectively (entries 8 and 9). Of the chiral diene ligands[18] examined (entries 10–12), Fc-tfb[19] showed the highest performance in terms of both catalytic activity and enantioselectivity to give 85% yield of triarylmethane **3aa** with 95% ee (entry 10).[20] With segphos[21] as a chiral ligand, the enantioselectivity was higher (96% ee), but the yield was lower (56%) (entry 13). Dioxane is a solvent of choice for the present reaction, the yield of **3aa** being lower in THF, toluene, and dichloroethane (entries 14–16). The reaction of morpholino-substituted diarylmethylamine **6a′** with the Rh/Fc-tfb catalyst in dioxane gave **3aa** with essentially the same enantioselectivity (94% ee) as **6a**, although the yield is slightly lower (entry 17).

NMR experiments showed that the addition of morpholine to **6a** in $CDCl_3$ brings about a rapid equilibration ($t_{1/2}$ < 1 h at 20 °C) with **6a′** and piperidine (see Supporting Information). Although *o*-quinone methide **1a** is not detected by NMR, it is likely that the equilibration proceeds through elimination–addition via the *o*-quinone methide intermediate, and the present Rh-catalyzed substitution of diarylmethylamine with arylboroxine also proceeds through the addition of an arylrhodium intermediate[22] to the *o*-quinone methide.

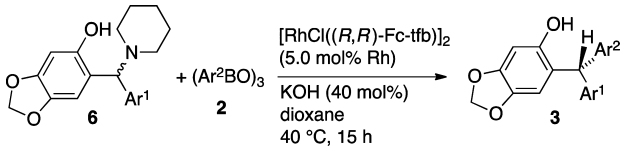
Several diarylmethylamines **6**, where one of the two aryl groups is 2-hydroxy-4,5-methylenedioxyphenyl, were subjected to the reaction with a variety of arylboroxines **2** under the conditions optimized for the reaction of diarylmethylamine **6a** with phenylboroxine (**2a**) (entry 10 in Table 1). The results summarized in Table 2 show that the enantioselectivity is generally high for most of the aryl groups in both diarylmethylamines **6** and arylboroxines **2** with some exceptions (entries 5, 6, 25, 26, and 27). One structural limitation of diarylmethylamine **6** is that the enantioselectivity is low with the ortho-substituted aryl group (entry 25). The arylation of diarylmethylamine **6b** with 4-methoxy- (**2e**) and 4-methylphenylboroxine (**2b**) was found to take place in the absence of rhodium catalyst to some extent,[23] which is in good agreement with the lower % ee observed in the asymmetric arylation with **2e** and **2b** (entries 5 and 6). The enantioselectivity was modest for the addition of 3-thienyl- and 3-furylboronic acids (entries 26 and 27).

The absolute configuration of the product **3bh** (Ar^1 = Ph, Ar^2 = 4-BrC_6H_4) was determined to be (*S*) by its X-ray crystallographic analysis.[24] The *S* configuration obtained with (*R*,*R*)-Fc-tfb is rationalized by the addition of aryl–rhodium intermediate to the quinone methide from its *si* face. The coordination with the other face is less favorable due to the steric repulsions between the carbonyl of quinone methide and one of the ferrocenyl groups on the diene ligand[25] (Scheme 2). All the products under the present conditions with (*R*,*R*)-Fc-tfb ligand are assumed to have the same configuration.

To generate the *o*-quinone methide intermediate efficiently under the present conditions, an electron-donating substituent on the 2-hydroxyphenyl group is necessary. Replacement of 4,5-methylenedioxy in **6a** by methyl made the diarylmethylamine **7a** much less reactive, and the yield of the triarylmethane product **8ai** is low even at higher temperature (70 °C) for a longer reaction time (Scheme 3). With MeO substitution, **7b** is more

DOI: 10.1021/jacs.5b03277
J. Am. Chem. Soc. 2015, 137, 7556–7559

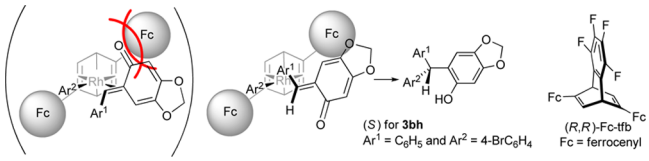
Table 2. Rhodium-Catalyzed Asymmetric Arylation of Diarylmethylamines 6 with Arylboroxines 2[a]



entry	4: Ar^1	2: Ar^2	3: yield (%)[b]	ee (%)[c]
1	**6a**: 4-$MeOC_6H_4$	**2a**: Ph	**3aa**: 85	95
2	**6a**: 4-$MeOC_6H_4$	**2b**: 4-MeC_6H_4	**3ab**: 91	90
3	**6a**: 4-$MeOC_6H_4$	**2c**: 3-$MeOC_6H_4$	**3ac**: 80	96
4	**6a**: 4-$MeOC_6H_4$	**2d**: 4-ClC_6H_4	**3ad**: 82	95
5	**6b**: Ph	**2e**: 4-$MeOC_6H_4$	**3be**: 94	59
6	**6b**: Ph	**2b**: 4-MeC_6H_4	**3bb**: 85	84
7[d]	**6b**: Ph	**2c**: 3-$MeOC_6H_4$	**3bc**: 99	95
8	**6b**: Ph	**2f**: 3-MeC_6H_4	**3bf**: 84	90
9	**6b**: Ph	**2g**: 4-FC_6H_4	**3bg**: 82	90
10	**6b**: Ph	**2d**: 4-ClC_6H_4	**3bd**: 83	95
11	**6b**: Ph	**2h**: 4-BrC_6H_4	**3bh**: 71	95
12	**6b**: Ph	**2i**: 4-$CF_3C_6H_4$	**3bi**: 82	97
13	**6b**: Ph	**2j**: 4-$MeOCOC_6H_4$	**3bj**: 65	95
14	**6b**: Ph	**2k**: 4-$NO_2C_6H_4$	**3bk**: 53	96
15	**6c**: 4-MeC_6H_4	**2a**: Ph	**3ca**: 85	90
16	**6d**: 4-$Me_2NC_6H_4$	**2a**: Ph	**3da**: 85	96
17	**6e**: 4-FC_6H_4	**2a**: Ph	**3ea**: 87	93
18	**6f**: 4-ClC_6H_4	**2a**: Ph	**3fa**: 86	94
19	**6g**: 4-BrC_6H_4	**2a**: Ph	**3ga**: 82	91
20	**6h**: 4-$CF_3C_6H_4$	**2a**: Ph	**3ha**: 81	94
21	**6i**: 4-$NO_2C_6H_4$	**2a**: Ph	**3ia**: 78	91
22	**6j**: 2-naphthyl	**2a**: Ph	**3ja**: 90	94
23[e,f]	**6j**: 2-naphthyl	**2a**: Ph	**3ja**: 88	94
24	**6k**: 2-thienyl	**2a**: Ph	**3ka**: 59	90
25	**6l**: 2-MeC_6H_4	**2a**: Ph	**3la**: 74	62
26[f]	**6a**: 4-$MeOC_6H_4$	**2l**: 3-thienyl[g]	**3al**: 77	50
27[f]	**6a**: 4-$MeOC_6H_4$	**2m**: 3-furyl[g]	**3am**: 35	67

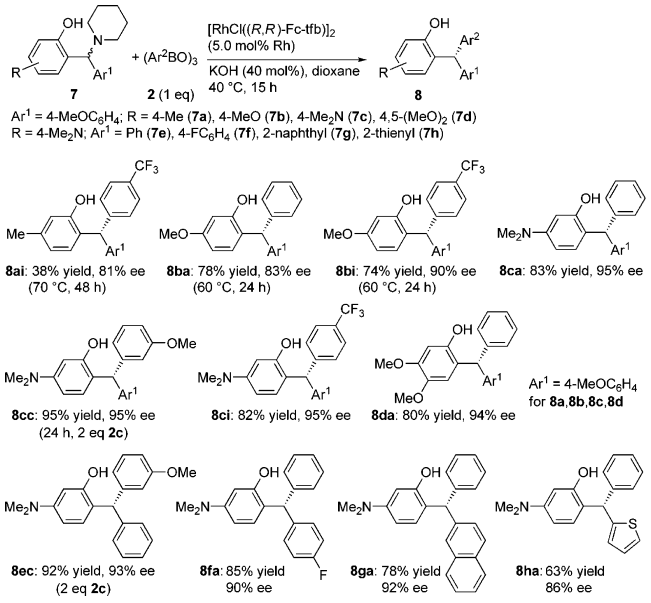
[a]Reaction conditions: diarylmethylamine **6** (0.12 mmol), arylboroxine **2** (0.36 mmol of B), $[RhCl((R,R)\text{-Fc-tfb})]_2$ (5 mol % of Rh), KOH (0.048 mmol), dioxane (1.0 mL) at 40 °C for 15 h. [b]Isolated yield. [c]The % ee was determined by HPLC on a chiral stationary phase column. [d]Boroxine **2c** (0.72 mmol of B). [e]Reaction of **6j** (2.0 mmol) with 3 mol % of the catalyst for 40 h. [f]With $[RhCl((S,S)\text{-Fc-tfb})]_2$. [g]The boronic acid (0.72 mmol) was used.

Scheme 2. Proposed Stereochemical Pathway for the Asymmetric Arylation of a Quinone Methide Generated from 6 with 2 Catalyzed by Rh/(*R*,*R*)-Fc-tfb

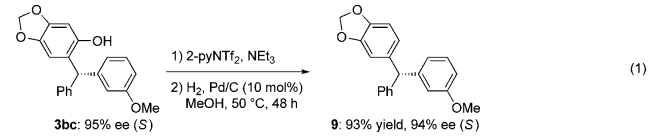


reactive than **7a**, but it is still necessary to heat the reaction. Under optimized conditions (at 60 °C for 24 h) **7b** gave a high yield of the triarylmethanes **8ba** and **8bi** albeit with lower enantioselectivity. Dimethylamino group can activate the diarylmethylamines **7c,e,f,g,h** to make their reactivity comparable with the methylenedioxy group. The reaction with boroxines **2** gave the corresponding triarylmethanes **8** with the enantioselectivity as high as for methylenedioxy substrates **6**.

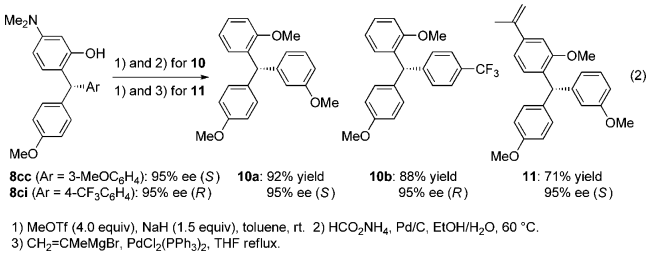
Scheme 3. Rhodium-Catalyzed Asymmetric Arylation of Diarylmethylamines 7 with Arylboroxines 2



The hydroxyl group in the triarylmethane products can be readily removed by palladium-catalyzed reduction of triflate[26,27] in a high yield. One example is shown in eq 1, where **3bc** was



reduced into **9** without serious loss of enantiomeric purity. Conversion of dimethylamino group in **8c** was also successful via trimethylammonium generated by treatment with MeOTf (eq 2). Methylation of the amino group and phenol oxygen in **8cc** followed by reductive removal of the ammonium[28] gave chiral trianisylmethane **10a**, where the three methoxy groups are located at ortho, meta, and para positions, respectively. The amino group was replaced by an alkenyl group by the palladium-catalyzed Grignard cross-coupling reaction[29] giving **11**. During these transformations, no racemization was observed.



In summary, we have developed a new type of catalytic asymmetric synthesis of chiral triarylmethanes, which is realized by a rhodium-catalyzed asymmetric substitution of diarylmethylamines with arylboron reagents. The reaction is assumed to proceed through *o*-quinone methide intermediates generated from diarylmethylamines. The enantioselectivity is generally high (≥90% ee) with the rhodium catalyst coordinated with a chiral diene ligand (Fc-tfb).

DOI: 10.1021/jacs.5b03277
J. Am. Chem. Soc. 2015, 137, 7556−7559

■ 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/jacs.5b03277.

■ AUTHOR INFORMATION

Corresponding Author

*tamioh@imre.a-star.edu.sg, chmtamh@nus.edu.sg

Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

We thank Institute of Materials Research and Engineering (IMRE) and National University of Singapore for supporting this research.

■ REFERENCES

(1) For pertinent reviews, see (a) Mondal, S.; Panda, G. *RSC Adv.* **2014**, *4*, 28317. (b) Nair, V.; Thomas, S.; Mathew, S. C.; Abhilash, K. G. *Tetrahedron* **2006**, *62*, 6731. For selected papers, see (c) Parai, M. K.; Panda, G.; Chaturvedi, V.; Manju, Y. K.; Sinha, S. *Bioorg. Med. Chem. Lett.* **2008**, *18*, 289. (d) Gibson, H. W.; Lee, S.-H.; Engen, P. T.; Lecavalier, P.; Sze, J.; Shen, Y. X.; Bheda, M. *J. Org. Chem.* **1993**, *58*, 3748. (e) Finocchiaro, P.; Gust, D.; Mislow, K. *J. Am. Chem. Soc.* **1974**, *96*, 3198.

(2) (a) Taylor, B. L. H.; Harris, M. R.; Jarvo, E. R. *Angew. Chem., Int. Ed.* **2012**, *51*, 7790. (b) Harris, M. R.; Hanna, L. E.; Greene, M. A.; Moore, C. E.; Jarvo, E. R. *J. Am. Chem. Soc.* **2013**, *135*, 3303.

(3) Zhou, Q.; Srinivas, H. D.; Dasgupta, S.; Watson, M. P. *J. Am. Chem. Soc.* **2013**, *135*, 3307.

(4) Matthew, S. C.; Glasspoole, B. W.; Eisenberger, P.; Crudden, C. M. *J. Am. Chem. Soc.* **2014**, *136*, 5828.

(5) Shi, B.-F.; Maugel, N.; Zhang, Y.-H.; Yu, J.-Q. *Angew. Chem., Int. Ed.* **2008**, *47*, 4882.

(6) (a) Sun, F.-L.; Zheng, X.-J.; Gu, Q.; He, Q.-L.; You, S.-L. *Eur. J. Org. Chem.* **2010**, 47. See also (b) Zhuo, M.-H.; Jiang, Y.-J.; Fan, Y.-S.; Gao, Y.; Liu, S.; Zhang, S. *Org. Lett.* **2014**, *16*, 1096.

(7) For pertinent reviews, see (a) Tian, P.; Dong, H.-Q.; Lin, G.-Q. *ACS Catal.* **2012**, *2*, 95. (b) Partyka, D. V. *Chem. Rev.* **2011**, *111*, 1529. (c) Berthon, G.; Hayashi, T. In *Catalytic Asymmetric Conjugate Reactions*; Córdova, A., Ed.; Wiley-VCH: Weinheim, Germany, 2010; Chapter 1, p 1. (d) Edwards, H. J.; Hargrave, J. D.; Penrose, S. D.; Frost, C. G. *Chem. Soc. Rev.* **2010**, *39*, 2093. (e) Johnson, J. B.; Rovis, T. *Angew. Chem., Int. Ed.* **2008**, *47*, 840. (f) Darses, S.; Genet, J.-P. *Eur. J. Org. Chem.* **2003**, 4313. (g) Hayashi, T.; Yamasaki, K. *Chem. Rev.* **2003**, *103*, 2829. (h) Fagnou, K.; Lautens, M. *Chem. Rev.* **2003**, *103*, 169. (i) Bolm, C.; Hildebrand, J. P.; Muñiz, K.; Hermanns, N. *Angew. Chem., Int. Ed.* **2001**, *40*, 3284.

(8) Early examples of addition to α,β-unsaturated ketones (a) Sakai, M.; Hayashi, H.; Miyaura, N. *Organometallics* **1997**, *16*, 4229. (b) Takaya, Y.; Ogasawara, M.; Hayashi, T.; Sakai, M.; Miyaura, N. *J. Am. Chem. Soc.* **1998**, *120*, 5579.

(9) Reviews on *o*-quinone methides (a) Van De Water, R. W.; Pettus, T. R. R. *Tetrahedron* **2002**, *58*, 5367. (b) Amouri, H.; Bras, J. L. *Acc. Chem. Res.* **2002**, *35*, 501. (c) Pathak, T. P.; Sigman, M. S. *J. Org. Chem.* **2011**, *76*, 9210. (d) Willis, N. J.; Bray, C. D. *Chem.—Eur. J.* **2012**, *18*, 9160. (e) Bai, W.-J.; David, J. G.; Feng, Z.-G.; Weaver, M. G.; Wu, K.-L.; Pettus, T. R. R. *Acc. Chem. Res.* **2014**, *47*, 3655.

(10) Jurd, L. *Tetrahedron* **1977**, *33*, 163.

(11) Itooka, R.; Iguchi, Y.; Miyaura, N. *J. Org. Chem.* **2003**, *68*, 6000.

(12) Hayashi, T.; Takahashi, M.; Takaya, Y.; Ogasawara, M. *J. Am. Chem. Soc.* **2002**, *124*, 5052.

(13) Luan, Y.; Schaus, S. E. *J. Am. Chem. Soc.* **2012**, *134*, 19965.

(14) Recent examples of the use of *o*-quinone methides for asymmetric catalysis (a) Selenski, C.; Pettus, T. R. R. *J. Org. Chem.* **2004**, *69*, 9196. (b) Zhang, Y.; Sigman, M. S. *J. Am. Chem. Soc.* **2007**, *129*, 3076. (c) Alden-Danforth, E.; Scerba, M. T.; Lectka, T. *Org. Lett.* **2008**, *10*, 4951. (d) Lv, H.; You, L.; Ye, S. *Adv. Synth. Catal.* **2009**, *351*, 2822. (e) Lv, H.; Jia, W.-Q.; Sun, L.-H.; Ye, S. *Angew. Chem., Int. Ed.* **2013**, *52*, 8607. (f) El-Sepelgy, O.; Haseloff, S.; Alamsetti, S. K.; Schneider, C. *Angew. Chem., Int. Ed.* **2014**, *53*, 7923. (g) Saha, S.; Schneider, C. *Chem.—Eur. J.* **2015**, *21*, 2348. (h) Hsiao, C.-C.; Raja, S.; Liao, H.-H.; Atodiresei, I.; Rueping, M. *Angew. Chem., Int. Ed.* **2015**, *54*, 5762. (i) Zhao, J.-J.; Sun, S.-B.; He, S.-H.; Wu, Q.; Shi, F. *Angew. Chem., Int. Ed.* **2015**, *54*, 5460.

(15) Cyclic boronates as precursors of *o*-quinone methides, see (a) Chambers, J. D.; Crawford, J.; Williams, H. W. R.; Dufresne, C.; Scheigetz, J.; Bernstein, M. A.; Lau, C. K. *Can. J. Chem.* **1992**, *70*, 1717. (b) Lau, C. K.; Mintz, M.; Bernstein, M. A.; Dufresne, C. *Tetrahedron Lett.* **1993**, *34*, 5527. (c) Bissada, S.; Lau, C. K.; Bernstein, M. A.; Dufresne, C. *Tetrahedron Lett.* **1994**, *35*, 3691.

(16) For a review, see Cardellicchio, C.; Capozzi, M. A. M.; Naso, F. *Tetrahedron: Asymmetry* **2010**, *21*, 507.

(17) (a) Jurd, L. *J. Heterocyclic Chem.* **1985**, *22*, 993. (b) Lavecchia, A.; Giovanni, C. D.; Cerchia, C.; Russo, A.; Russo, G.; Novellino, E. *J. Med. Chem.* **2013**, *56*, 2861. (c) von Strandtmann, M.; Cohen, M. P.; Shavel, J., Jr. *Tetrahedron Lett.* **1965**, *6*, 3103.

(18) 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**, 1345. (d) Feng, X.; Du, H. *Asian J. Org. Chem.* **2012**, *1*, 204.

(19) (a) Nishimura, T.; Kumamoto, H.; Nagaosa, M.; Hayashi, T. *Chem. Commun.* **2009**, 5713. (b) Nishimura, T.; Noishiki, A.; Ebe, Y.; Hayashi, T. *Angew. Chem., Int. Ed.* **2013**, *52*, 1777. (c) Nishimura, T.; Ashouri, A.; Ebe, Y.; Maeda, Y.; Hayashi, T. *Tetrahedron: Asymmetry* **2012**, *23*, 655. (d) Sasaki, K.; Hayashi, T. *Tetrahedron Asymmetry* **2012**, *23*, 373. (e) Lim, K. M.-H.; Hayashi, T. *J. Am. Chem. Soc.* **2015**, *137*, 3201 and references cited.

(20) The yield of the phenylation product **3aa** was lower (47%) with a smaller amount (0.06 mmol (0.18 mmol of B)) of $(PhBO)_3$. The reaction of **6a** with $PhB(OH)_2$ and $PhBF_3K$ in place of $(PhBO)_3$ under the same conditions for entry 10 in Table 1 gave **3aa**, in 78% yield (95% ee) and in <3% yield, respectively.

(21) Saito, T.; Yokozawa, T.; Ishizaki, T.; Moroi, T.; Sayo, N.; Miura, T.; Kumobayashi, H. *Adv. Synth. Catal.* **2001**, *343*, 264.

(22) For the catalytic cycle of Rh-catalyzed 1,4-addition of organoboronic acids, see ref 12.

(23) In the absence of rhodium catalyst, the reactions in entries 5 and 6 under otherwise same conditions gave the arylation products in 58% (**3be**) and 5% (**3bb**) yields, respectively. The rhodium-catalyzed reaction at 23 °C gave **3be** with 72% ee albeit in a low yield (40%).

(24) The details are described in Supporting Information.

(25) The rationalization of stereochemical pathway using this type of model has been always successful (ref 18b). See also Hayashi, T.; Ueyama, K.; Tokunaga, N.; Yoshida, K. *J. Am. Chem. Soc.* **2003**, *125*, 11508.

(26) Wang, Z.; Ai, F.; Wang, Z.; Zhao, W.; Zhu, G.; Lin, Z.; Sun, J. *J. Am. Chem. Soc.* **2015**, *137*, 383.

(27) For reviews on the conversion of aryl triflates, see (a) Ritter, K. *Synthesis* **1993**, 735. (b) Doucet, H. *Eur. J. Org. Chem.* **2008**, 2013. (c) Corbet, J.-P.; Mignani, G. *Chem. Rev.* **2006**, *106*, 2651.

(28) For Pd-catalyzed reduction of aryl halides, see (a) Rajagopal, S.; Spatola, A. F. *J. Org. Chem.* **1995**, *60*, 1347. (b) Cellier, P. P.; Spindler, J.-F.; Taillefer, M.; Cristau, H.-J. *Tetrahedron Lett.* **2003**, *44*, 7191. (c) Arcadi, A.; Cerichelli, G.; Chiarini, M.; Vico, R.; Zorzan, D. *Eur. J. Org. Chem.* **2004**, 3404.

(29) For cross-coupling of $ArNMe_3OTf$, see (a) Reeves, J. T.; Fandrick, D. R.; Tan, Z.; Song, J. J.; Lee, H.; Yee, N. K.; Senanayake, C. H. *Org. Lett.* **2010**, *12*, 4388. (b) Guo, W.-J.; Wang, Z.-X. *Tetrahedron* **2013**, *69*, 9580.

DOI: 10.1021/jacs.5b03277
J. Am. Chem. Soc. 2015, 137, 7556−7559