J|A|C|S
COMMUNICATIONS

Published on Web 02/03/2006

Rhodium-Catalyzed Asymmetric Hydroarylation of Diphenylphosphinylallenes with Arylboronic Acids

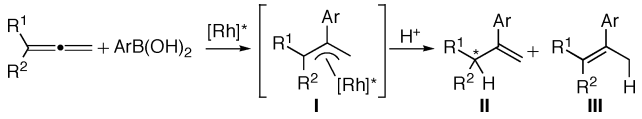
Takahiro Nishimura, Sho Hirabayashi, Yuichi Yasuhara, and Tamio Hayashi*

Department of Chemistry, Graduate School of Science, Kyoto University, Sakyo-ku, Kyoto 606-8502, Japan

Received December 26, 2005; E-mail: thayashi@kuchem.kyoto-u.ac.jp

Recently, it has been disclosed that chiral rhodium complexes efficiently catalyze the asymmetric addition of arylboronic acids to activated alkenes offering one of the best ways to construct a new C−C bond enantioselectively.[1,2] In this context, we next focused on the asymmetric arylation of allenes. It has been known that arylmetal species add to allenes to generate π-allylmetal species.[3] As shown in Scheme 1, it would be possible to create a stereogenic carbon center if the chiral π-allylrhodium intermediate (**I**), formed by the reaction of a 1,1-disubstituted allene and an arylrhodium species, undergoes the protonation regioselectively as well as enantioselectively.[4] This asymmetric transformation leading to chiral alkenes (**II**) is difficult due to the competitive formation of internal achiral ones (**III**), and to the best of our knowledge, there have been no reports on the catalytic asymmetric hydroarylation of allenes.[5] Here we report that it is realized by rhodium-catalyzed addition of arylboronic acids to allenes bearing phosphine oxide,[6] which produces chiral allylic phosphine oxides of high enantiomeric purity.

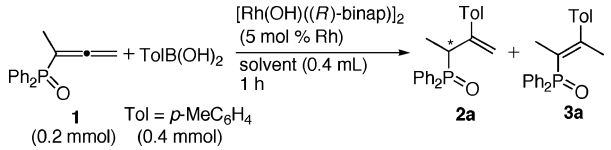
Scheme 1



Phosphinylallenes are stable compounds and readily available from chlorophosphines and propargylic alcohols in one step.[7] Our initial studies were focused on the asymmetric hydroarylation of 3-(diphenylphosphinyl)-3-methyl-1,2-butadiene (**1**) in the presence of chiral rhodium complexes directed toward the catalytic synthesis of chiral allylic phosphine oxide **2a**, which is a useful intermediate for chiral tertiary allylphosphines or chiral alkenes (Table 1).[8,9] Treatment of allene **1** with *p*-tolylboronic acid (2 equiv) in the presence of [Rh(OH)((*R*)-binap)]$_2$[10] (5 mol % of Rh) in 1,4-dioxane at 100 °C for 1 h gave the hydroarylation product **2a** with 89% ee together with a considerable amount of **3a** (total yield 92%, **2a**/**3a** = 75/25, entry 1). The reaction temperature did not have a significant influence on the selectivity (entry 2), but the change of the solvent to THF markedly improved the regioselectivity as well as the enantioselectivity, giving **2a** with 97% ee (total yield 97%, **2a**/**3a** = 96/4, entry 3). [Rh(OH)(cod)]$_2$ as a catalyst precursor can be used as well in combination with (*R*)-binap (entry 4).

As shown in Table 2, aryl groups substituted with either electron-donating or -withdrawing groups were introduced onto allene **1** with high enantioselectivity to give the corresponding allylic phosphine oxides **2a**−**2f** with 96−98% ee (entries 1−7). A high yield of **2a** was obtained without loss of the enantioselectivity even in the presence of a reduced amount of the catalyst (1 mol %) (entry 2). The configuration of **2e** was determined to be *S* by X-ray crystallographic analysis.[11] High enantio- and regioselectivities were also observed for allenes **4** and **6**, which are substituted with ethyl and butyl, respectively (entries 8 and 9). On the other hand, allene **8** bearing a phenyl group gave **9** in a low yield with lower enantiomeric excess (40% yield, 69% ee), internal alkene **10** being accompanied in 45% yield (entry 10). A bulkier substituent (*tert*-butyl) on **11** completely changed the regioselectivity to give **12** in 91% yield (entry 11).

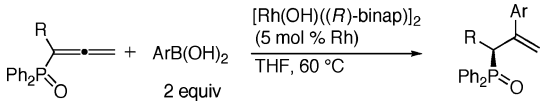
Table 1. Rhodium-Catalyzed Asymmetric Hydroarylation of **1**: Solvent Effect



entry	solvent	temp (°C)	yield (**2a**+**3a**) (%)[a]	**2a**/**3a**[b]	ee (%) of **2a**[c]
1	dioxane	100	92	75/25	89
2	dioxane	60	92	71/29	90
3	THF	60	97	96/4	97
4[d]	THF	60	96	96/4	97

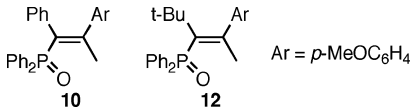
[a] Isolated yield. [b] Determined by ^{1}H NMR. [c] Determined by HPLC analysis with chiral stationary phase column: Chiralcel OJ-H. [d] [Rh(OH)(cod)]$_2$ (5 mol % of Rh) and (*R*)-binap (5.5 mol %) were used instead of [Rh(OH)((*R*)-binap)]$_2$.

Table 2. Rhodium-Catalyzed Asymmetric Hydroarylation of Diphenylphosphinylallenes: Scope of Arylboronic Acids and Allenes



entry	R	Ar	time (h)	yield (%)[a]	ee (%)[b]
1	**1**: Me	*p*-MeC$_6$H$_4$	1	**2a**: 85	97 (*S*)
2[c]	**1**: Me	*p*-MeC$_6$H$_4$	6	**2a**: 88	97 (*S*)
3	**1**: Me	*p*-MeOC$_6$H$_4$	1	**2b**: 89	96 (*S*)
4	**1**: Me	C$_6$H$_5$	1	**2c**: 90	96 (*S*)
5	**1**: Me	2-naphthyl	1	**2d**: 94	98 (*S*)
6	**1**: Me	*p*-ClC$_6$H$_4$	5	**2e**: 91	97 (*S*)
7	**1**: Me	*p*-CF$_3$C$_6$H$_4$	12	**2f**: 85	96 (*S*)
8	**4**: Et	*p*-MeOC$_6$H$_4$	1	**5**: 94	97 (*S*)
9	**6**: Bu	*p*-MeOC$_6$H$_4$	1	**7**: 88	96 (*S*)
10	**8**: Ph	*p*-MeOC$_6$H$_4$	1	**9**: 40, **10**: 45	69 (*S*)
11	**11**: t-Bu	*p*-MeOC$_6$H$_4$	1	**12**: 91	

[a] Isolated yields after removal of a small amount of internal alkenes by column chromatography on silica gel. [b] Determined by HPLC. Absolute configuration of **2e** was determined by X-ray crystallographic analysis. For others, they were assigned by consideration of the stereochemical pathway. [c] 1 mol % of Rh was used.



10.1021/ja058763f CCC: $33.50

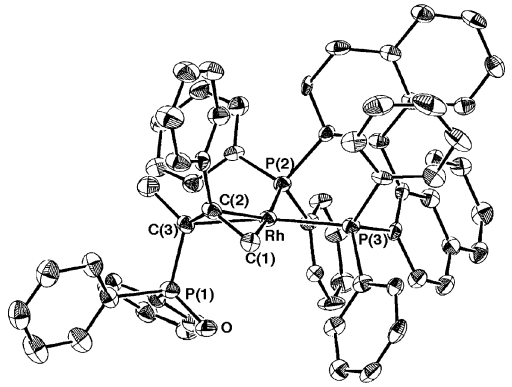
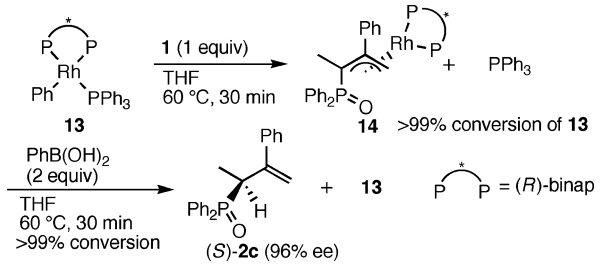


Figure 1. ORTEP illustration of η^3-allylrhodium(I) complex **14** with thermal ellipsoids drawn at 50% probability (hydrogens are omitted).

Scheme 2



NMR studies on a sequence of stoichiometric reactions starting from phenylrhodium complex [RhPh(PPh$_3$)((*R*)-binap)][10] (**13**) (Scheme 2) provided us with a significant insight into the catalytic cycle of the present reaction. Treatment of **13** with **1** (1.0 equiv) in THF-d_8 at 60 °C for 30 min brought about selective formation of a new rhodium complex. ^{31}P NMR of the reaction mixture consisted of two dd's, 34.9 (J_{P-P} = 13, J_{Rh-P} = 3 Hz), 46.9 (J_{Rh-P} = 198 Hz, J_{P-P} = 35 Hz), and one ddd 38.4 (J_{Rh-P} = 197 Hz, J_{P-P} = 35, 13 Hz) as well as a peak of free PPh$_3$, which is consistent with formation of π-allylrhodium complex **14**. The structure of **14** was successfully determined by X-ray crystallographic analysis.[12] As shown in Figure 1, two phosphorus atoms (P(2), P(3)) of (*R*)-binap and π-allyl carbons (C(1), C(3)) constitute square planar orientation around the Rh center. The diphenylphosphinyl substituent on the π-allyl is located anti with respect to the phenyl group on the central carbon C(2). This orientation is probably due to the steric effect by one of the phenyl rings of the binap ligand. The absolute configuration of the π-allyl moiety in **14** is 2*R*,3*R*. Addition of phenylboronic acid (2.0 equiv) to the THF-d_8 solution containing **14** and PPh$_3$ gave, after heating at 60 °C for 30 min, hydrophenylation product **2c** and phenylrhodium complex **13**. The isolated **2c** (93% yield) was an *S* isomer of 96% ee, which is the same as that obtained in the catalytic reaction.

Thus, we succeeded in establishing the catalytic cycle which involves the addition of an arylrhodium species to allene, forming a π-allylrhodium species, and protonolysis[13] of the π-allylrhodium, giving hydroarylation product, followed by transmetalation, regenerating the arylrhodium intermediate. The same stereochemical outcome (96% ee *S*) observed in the catalytic reaction and the stoichiometric reaction imply that the protonation in the catalytic system occurs after the equilibration into a thermodynamically stable π-allylrhodium intermediate (such as **14**), and the *R* configuration at C(3) of the π-allyl complex **14** indicates that the π-allyl undergoes protonation from the same side as rhodium, although the detailed mechanism of the protonation remains to be clarified.[14]

In summary, highly enantioselective hydroarylation (up to 98% ee) of diphenylphosphinylallenes with arylboronic acids was realized. We succeeded in the structural determination of the π-allylrhodium intermediate to establish the catalytic cycle of the reaction.

Acknowledgment. This work has been supported in part by a Grant-in-Aid for Scientific Research, the Ministry of Education, Culture, Sports, Science and Technology, Japan (Priority Areas "Advanced Molecular Transformations of Carbon Resources").

Supporting Information Available: Experimental procedures and spectroscopic and analytical data for the substrates and products (PDF) and X-ray data files (CIF). This material is available free of charge via the Internet at http://pubs.acs.org.

References

(1) (a) Hayashi, T.; Yamasaki, K. *Chem. Rev.* **2003**, *103*, 2829. (b) Hayashi, T *Bull. Chem. Soc. Jpn.* **2004**, *77*, 13. (c) Hayashi, T. *Pure Appl. Chem.* **2004**, *76*, 465. (d) Darses, S.; Genet, J.-P. *Eur. J. Org. Chem.* **2003**, 4313. (e) Fagnou, K.; Lautens, M. *Chem. Rev.* **2003**, *103*, 169. (f) Takaya, Y.; Ogasawara, M.; Hayashi, T.; Sakai, M.; Miyaura, N. *J. Am. Chem. Soc.* **1998**, *120*, 5579.

(2) For recent representative examples of rhodium-catalyzed asymmetric 1,4-addition of arylboronic acids, see: (a) Hayashi, T.; Ueyama, K.; Tokunaga, N.; Yoshida, K. *J. Am. Chem. Soc.* **2003**, *125*, 11508. (b) Shintani, R.; Okamoto, K.; Hayashi, T. *Org. Lett.* **2005**, *7*, 4757. (c) Kuriyama, M.; Nagai, K.; Yamada, K.-i.; Miwa, Y.; Taga, T.; Tomioka, K. *J. Am. Chem. Soc.* **2002**, *124*, 8932. (d) Itooka, R.; Iguchi, Y.; Miyaura, N. *J. Org. Chem.* **2003**, *68*, 6000. (e) Duursma, A.; Boiteau, J.-G.; Lefort, L.; Boogers, J. A. F.; de Vries, A. H. M.; de Vries, J. G.; Minnaard, A. J.; Feringa, B. L. *J. Org. Chem.* **2004**, *69*, 8045. (f) Ma, Y.; Song, C.; Ma, C.; Sun, Z.; Chai, Q.; Andrus, M. B. *Angew. Chem., Int. Ed.* **2003**, *42*, 5871. (g) Belyk, K. M.; Beguin, C. D.; Palucki, M.; Grinberg, N.; DaSilva, J.; Askin, D.; Yasuda, N. *Tetrahedron Lett.* **2004**, *45*, 3265. (h) Mauleón, P.; Carretero, J. C. *Org. Lett.* **2004**, *6*, 3195. (i) Paquin, J.-F.; Defieber, C.; Stephenson, C. R. J.; Carreira, E. M. *J. Am. Chem. Soc.* **2005**, *127*, 10850.

(3) (a) Zimmer, R.; Dinesh, C. U.; Nandanan, E.; Khan, F. A. *Chem. Rev.* **2000**, *100*, 3067. (b) Ma, S. *Chem. Rev.* **2005**, *105*, 2829.

(4) For rhodium-catalyzed asymmetric arylation of activated alkenes via enantioselective protonation, see: (a) Reetz, M. T.; Moulin, D.; Gosberg, A. *Org. Lett.* **2001**, *3*, 4083. (b) Chapman, C. J.; Wadsworth, K. J.; Frost, C. G. *J. Organomet. Chem.* **2003**, *680*, 206. (c) Moss, R. J.; Wadsworth, K. J.; Chapman, C. J.; Frost, C. G. *Chem. Commun.* **2004**, 1984. (d) Navarre, L.; Darses, S.; Genet, J.-P. *Angew. Chem., Int. Ed.* **2004**, *43*, 719. (e) Sibi, M. P.; Tadamidani, H.; Patil, K. *Org. Lett.* **2005**, *7*, 2571.

(5) For palladium-catalyzed asymmetric addition of Meldrum acids and azlactones to allenes, see: (a) Trost, B. M.; Jäkel, C.; Plietker, B. *J. Am. Chem. Soc.* **2003**, *125*, 4438. For palladium-catalyzed enantioselective hetero- and carboannulation involving allenes, see: (b) Larock, R. C.; Zenner, J. M. *J. Org. Chem.* **1995**, *60*, 482. (c) Zenner, J. M.; Larock, R. C. *J. Org. Chem.* **1999**, *64*, 7312. (d) Hiroi, K.; Kato, F.; Yamagata, A. *Chem. Lett.* **1998**, 397. (e) Hiroi, K.; Hiratsuka, Y.; Watanabe, K.; Abe, I.; Kato, F.; Hiroi, M. *Tetrahedron: Asymmetry* **2002**, *13*, 1351. (f) Kato, F.; Hiroi, K. *Chem. Pharm. Bull.* **2004**, *52*, 95. (g) Ma, S.; Shi, Z.; Wu, S. *Tetrahedron: Asymmetry* **2001**, *12*, 193.

(6) Palladium-catalyzed addition of arylboronic acids to allenes: (a) Oh, C. H.; Ahn, T. W.; Reddy, R. V. *Chem. Commun.* **2003**, 2622. (b) Gupta, A. K.; Rhim, C. Y.; Oh, C. H. *Tetrahedron Lett.* **2005**, *46*, 2247. (c) Ma, S.; Jiao, N.; Ye, L. *Chem.—Eur. J.* **2003**, *9*, 6049. (d) Yoshida, M.; Gotou, T.; Ihara, M. *Chem. Commun.* **2004**, 1124. (e) Hopkins, C. D.; Malinakova, H. C. *Org. Lett.* **2004**, *6*, 2221. (f) Hopkins, C. D.; Guan, L.; Malinakova, H. C. *J. Org. Chem.* **2005**, *70*, 6848.

(7) (a) Boisselle, A. P.; Meinhardt, N. A. *J. Org. Chem.* **1962**, *27*, 1828. For representative examples involving carbometalation to phosphinylallenes, see: (b) Rubin, M.; Markov, J.; Chuprakov, S.; Wink, D. J.; Gevorgyan, V. *J. Org. Chem.* **2003**, *68*, 6251. (c) Berlan, J.; Battioni, J.-P.; Koosha, K. *Tetrahedron Lett.* **1976**, 3351.

(8) For representative examples of the synthesis of chiral allylic phosphine oxides, see: (a) Liron, F.; Knochel, P. *Chem. Commun.* **2004**, 304. (b) Demay, S.; Harms, K.; Knochel, P. *Tetrahedron Lett.* **1999**, *40*, 4981.

(9) Sadow, A. D.; Haller, I.; Fadini, L.; Togni, A. *J. Am. Chem. Soc.* **2004**, *126*, 14704.

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

(11) The Flack parameter is −0.03(5) with this configuration: Flack, H. D. *Acta Crystallogr., Sect. A* **1983**, *39*, 876.

(12) For examples of the synthesis of π-allylrhodium(I) complexes from rhodium complexes and allenes, see: (a) Osakada, K.; Choi, J.-C.; Yamamoto, T. *J. Am. Chem. Soc.* **1997**, *119*, 12390. (b) Choi, J.-C.; Osakada, K.; Yamamoto, T. *Organometallics* **1998**, *17*, 3044.

(13) The arylation of **1** with *p*-tolylboroxine in the presence of D_2O gave (2-deuterio-3-*p*-tolylbut-3-en-2-yl)diphenylphosphine oxide **2a(D)** (82% D) in 91% yield.

(14) A diphenylphosphinyl group may play an important role in the hydroarylation of allenes to obtain the desired adduct selectively. For example, the reaction of 1-methyl-1-(trimethylsilyl)allene with *p*-tolylboronic acid did not give the desired product at all under the same reaction conditions.

JA058763F