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Catalytic Cycle of Rhodium-Catalyzed Asymmetric 1,4-Addition of Organoboronic Acids. Arylrhodium, Oxa-π-allylrhodium, and Hydroxorhodium Intermediates

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Abstract: The catalytic cycle of asymmetric 1,4-addition of phenylboronic acid to an α,β-unsaturated ketone catalyzed by a rhodium−binap complex was established by use of $RhPh(PPh_3)$(binap) as a key intermediate. The reaction proceeds through three intermediates, phenylrhodium, oxa-π-allylrhodium, and hydroxorhodium complexes, all of which were observed in NMR spectroscopic studies. The transformations between the three intermediates, that is, insertion, hydrolysis, and transmetalation, were also observed. On the basis of the catalytic cycle, a more active chiral catalyst, $[Rh(OH)(binap)]_2$, was found and used successfully for the asymmetric 1,4-addition reactions.

Introduction

Growing attention is currently devoted to development of new reactions by using a combination of a rhodium catalyst and organoboron reagents. The rhodium-catalyzed reaction has realized the addition of arylboronic acids and their analogues to the carbon−carbon double bond,[1−3] carbon−carbon triple bond,[4] and carbon−heteroatom double bonds.[5,6] One of the most exciting applications of the rhodium-catalyzed addition reactions is an extension to catalytic asymmetric carbon−carbon bond-forming reactions.[7] The rhodium-catalyzed asymmetric 1,4-addition of organoboronic acids[8−12] has several unique advantages over other asymmetric 1,4-addition reactions[13] in that (1) the enantioselectivity is very high, usually over 95%, (2) the reaction is carried out in an aqueous solvent, (3) the reaction temperature is not very low, usually between 60 and 100 °C, (4) a variety of sp^2 carbon groups (aryl and alkenyl groups) can be introduced, and (5) the asymmetric addition takes place on various types of electron-deficient olefins including α,β-unsaturated ketones, esters, amides, phosphonates, and nitroalkenes.[12] A typical example is the reaction of 2-cyclohexenone (**1a**) with phenylboronic acid (**2m**) in the presence of 3 mol % of Rh(acac)(binap) as a catalyst in dioxane/H_2O (10/1) at 100 °C, which gives the phenylation product **3am** of 97% ee[8] (Scheme 1). The catalytic cycle of the rhodium-catalyzed 1,4-addition of arylboronic acid has been proposed to involve (a) transmetalation of an aryl group from boron to rhodium, (b) insertion of enone into the aryl−rhodium bond forming a rhodium enolate, and (c) its hydrolysis giving the 1,4-addition product and hydroxorhodium species.[1,8−10] However, there have been no reports to date on isolation of any intermediates or observation of transformation from one intermediate to another in the catalytic cycle. Here we report our successful studies on the mechanism which clearly establish the catalytic cycle of the rhodium-catalyzed 1,4-addition. The reaction proceeds through three intermediates, phenylrhodium, oxa-π-allylrhodium, and hydroxorhodium species (Scheme 2), all of which have been observed in NMR spectroscopic studies. The mechanistic

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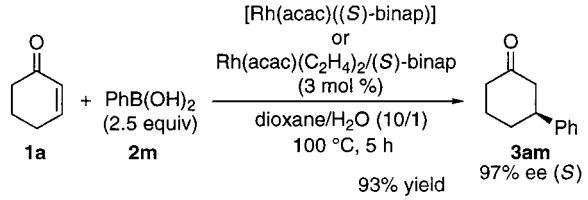
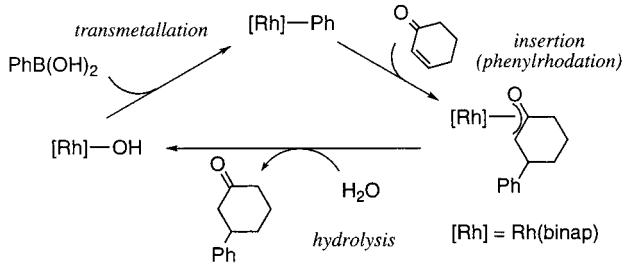
10.1021/ja012711i CCC: $22.00

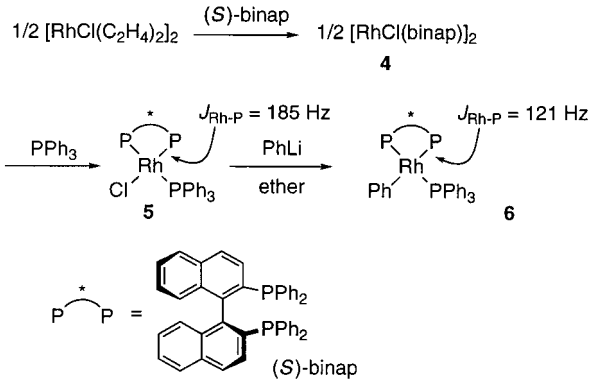
Scheme 1



Scheme 2



Scheme 3



studies have led to the discovery of a rhodium catalyst that is more catalytically active than Rh(acac)(binap).

Results and Discussion

As a key intermediate in the catalytic cycle, a square-planar rhodium(I) complex $RhPh(PPh_3)((S)\text{-binap})$ (**6**), which contains a phenyl−rhodium bond and (*S*)-binap as a chelating bisphosphine ligand, was prepared by phenylation of chloro−rhodium bond in $RhCl(PPh_3)((S)\text{-binap})$ (**5**) with phenyllithium in ether[14] (Scheme 3). Triphenylphosphine ligand was used as the third ligand, which stabilizes the phenylrhodium(I) complex. In the absence of triphenylphosphine, monomeric phenylrhodium species were hardly obtained. The phenylrhodium complex **6** was fully characterized by ^{31}P NMR. Three phosphorus atoms appear as three ddd's (see A in Figure 1), the coupling constants, $J_{P-P,trans} = 324$ Hz, $J_{P-P,cis} = 39$ and 30 Hz, and $J_{P-Rh} = 178$, 170, and 121 Hz, being characteristic of square-planar rhodium complexes coordinated with three unequivalent phosphorus atoms. The coupling constant, 185 Hz, between rhodium and the central phosphorus atom in the chloride complex **5** was decreased to 121 Hz by conversion into phenyl complex **6**, indicating that the chloride was replaced by a phenyl group that has a greater trans influence than chloride.[15]

The phenylrhodium complex **6** was allowed to react with an excess (4 equiv to **6**) of 2-cyclohexenone (**1a**) in dioxane/H_2O (10/1) at 100 °C for 1 h. This stoichiometric reaction gave a 64% yield of 3-phenylcyclohexanone (**3am**), which is an (*S*) isomer of 98.8% ee (Scheme 4). The high enantioselectivity and the same absolute configuration as that observed in the catalytic reaction[8] (Scheme 1) may indicate that the catalytic cycle involves the phenylrhodium species as a key intermediate. The phenylrhodium complex **6** was found to be active as a catalyst for the reaction of **1a** with phenylboronic acid (**2m**). The catalytic activity and enantioselectivity of **6** are essentially the same as those of the acetylacetonato rhodium complex, Rh(acac)((*S*)-binap), or that generated in situ from $Rh(acac)(C_2H_4)_2$ and (*S*)-binap,[8] the yield (94%) and the enantiomeric purity (98.6% ee) of **3am** being a little higher than those observed with the rhodium acetylacetonato catalyst.

NMR spectroscopic studies on a sequence of reactions starting with the phenylrhodium complex **6** established the catalytic cycle shown in Scheme 2. Thus, in an NMR sample tube, a solution of **6** (0.05 M) in THF was prepared, whose ^{31}P NMR is shown as spectrum A in Figure 1. To the solution was added 5 equiv of *tert*-butyl vinyl ketone at 25 °C. The three ddd resonances assigned to the phenyl complex **6** were gradually replaced by new signals. The ^{31}P NMR after 1 h, which is shown as spectrum B in Figure 1, demonstrates the formation of two species in a ratio of 2 to 1. Both isomers have two dd's, 37.9 ($J_{P-Rh} = 186$ Hz, $J_{P-Pcis} = 45$ Hz) and 48.4 ppm ($J_{P-Rh} = 222$ Hz, $J_{P-Pcis} = 45$ Hz) for the major isomer and 40.8 ($J_{P-Rh} = 182$ Hz, $J_{P-Pcis} = 45$ Hz) and 49.5 ppm ($J_{P-Rh} = 228$ Hz, $J_{P-Pcis} = 45$ Hz) for the minor isomer. A singlet assignable to triphenylphosphine free from rhodium was also observed at −4.5 ppm. The new resonances, two sets of two dd's, can be assigned to two diastereomeric oxa-π-allylrhodium complexes **7** and **7′** (Scheme 5). The structure of the oxa-π-allylrhodium complexes was confirmed by comparison of the ^{31}P NMR spectra with those of the authentic samples prepared by the reaction of $[RhCl(binap)]_2$ with potassium enolate of *tert*-butyl 2-phenylethyl ketone according to the procedures reported for the preparation of oxa-π-allylrhodium complexes from $[RhCl(PR_3)_2]_2$ and potassium enolates.[16] It should be noted that complex **7** adopts the oxa-π-allyl structure, not that of rhodium enolate[17] or α-rhodioketone, even in the presence of triphenylphosphine.

Addition of water (10 equiv to Rh) to the THF solution containing the oxa-π-allylrhodium complexes **7** and **7′** at 25 °C immediately generated a new rhodium species (spectrum C in Figure 1), which is assigned to be hydroxorhodium complex **8** (Scheme 6). A singlet for free triphenylphosphine stayed at the same high field. The doublet of ^{31}P NMR appearing at a low field, 55.0 ppm ($J_{P-Rh} = 186$ Hz) and a singlet in a high field (−1.90 ppm) observed in its ^1H NMR are characteristic of hydroxo-bridged rhodium dimer complexes.[18] The identical hydroxorhodium complex coordinated with binap **8** can be readily obtained by treatment of 1,5-cyclooctadiene complex $[Rh(OH)(cod)]_2$[19] with (*S*)-binap in benzene or by the reaction

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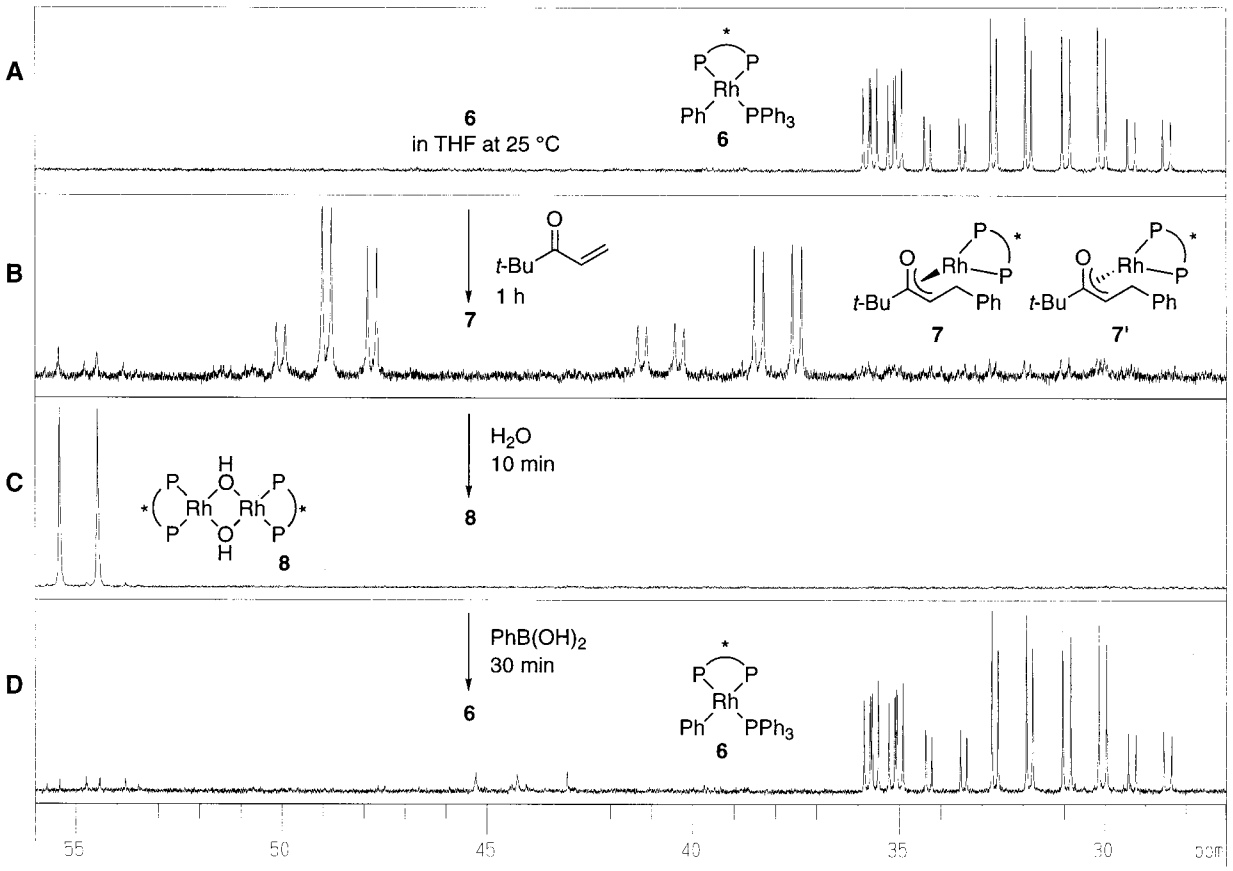
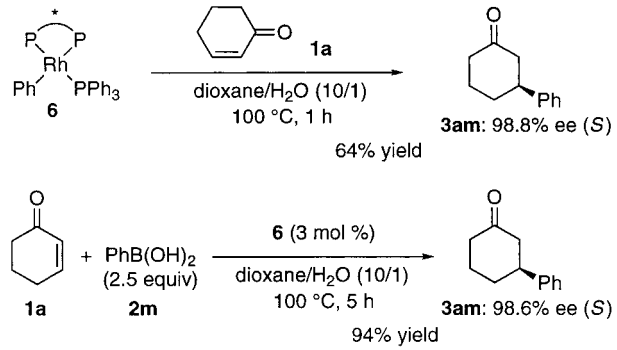
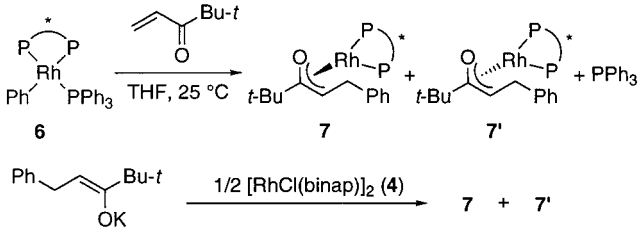


Figure 1. ^{31}P NMR spectra (at 202 MHz in THF at 25 °C) of rhodium complexes observed in the reactions starting from phenylrhodium **6**. (A) Phenylrhodium complex **6**. (B) Addition of *tert*-butyl vinyl ketone to **A** giving oxa-π-allylrhodium complexes **7** and **7′**. (C) Addition of water to **B** giving hydroxorhodium **8**. (D) Addition of phenylboronic acid to **C** giving phenylrhodium **6**.

Scheme 4



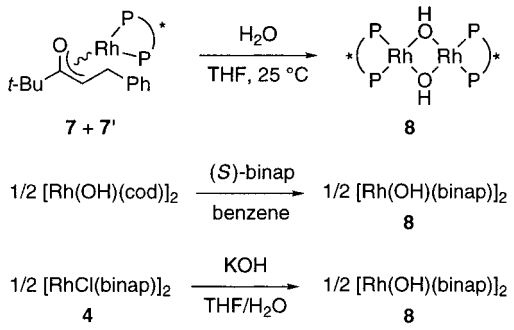
Scheme 5



of [RhCl((*S*)-binap)]$_2$ (**4**) with potassium hydroxide in aqueous THF. The pure sample of **8** is obtained by recrystallization from benzene and ethanol.

Transmetalation of a phenyl group from boron to rhodium was observed on addition of an excess of phenylboronic acid (**2m**) to the THF solution of the hydroxorhodium complex **8** obtained by the hydrolysis of the oxa-π-allylrhodium complexes

Scheme 6

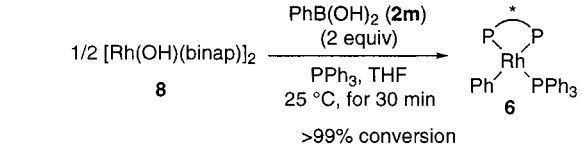


7 and **7′**. The transmetalation is fast at 25 °C, the doublet ascribed to the hydroxorhodium complex **8** being completely replaced by the phenylrhodium complex **6** within 30 min, which is shown as spectrum D in Figure 1. The triphenylphosphine, which was free from rhodium in the oxa-π-allyl complexes **7** and the hydroxo complex **8**, came back to the rhodium at the transmetalation. In a separate experiment with an isolated hydroxo complex **8** and 2 equiv of phenylboronic acid (**2m**) in THF, it was confirmed that the transmetalation is completed in 30 min at 25 °C (Scheme 7).[20]

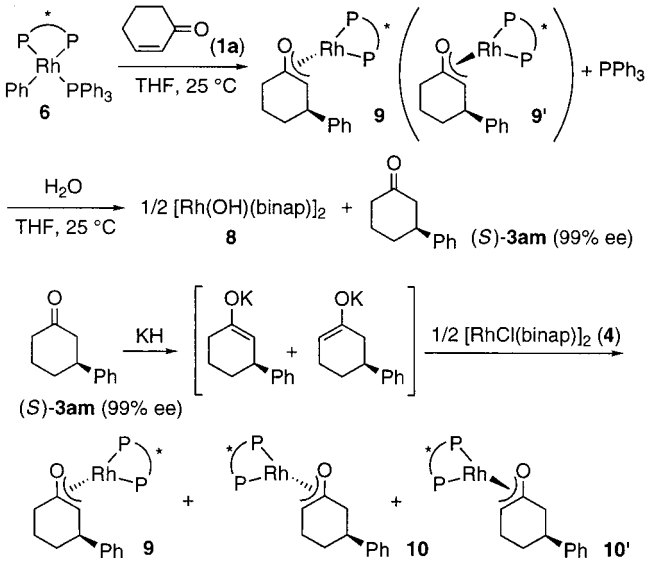
As described above in the reactions shown in Figure 1 and Schemes 5−7, which were carried out in one NMR sample tube,

(20) Miyaura and Suzuki reported the transmetalation of an alkenyl group from boron to palladium(II) complexes containing Pd−O bonds in their mechanistic studies on palladium-catalyzed cross-coupling: (a) Miyaura, N.; Yamada, K.; Suginome, H.; Suzuki, A. *J. Am. Chem. Soc.* **1985**, *107*, 972. (b) Miyaura, N.; Suzuki, A. *Chem. Rev.* **1995**, *95*, 2457. (c) Suzuki, A. *Acc. Chem. Res.* **1982**, *15*, 178.

Scheme 7



Scheme 8



we have succeeded in observing all three intermediates and all three reaction steps in the catalytic cycle (Scheme 2), namely, (a) insertion of an α,β-unsaturated ketone into the phenyl−rhodium bond forming oxa-π-allylrhodium, (b) hydrolysis of oxa-π-allylrhodium with water giving hydroxorhodium, and (c) transmetalation of a phenyl group from phenylboronic acid to hydroxorhodium to regenerate the starting phenylrhodium complex. All reactions proceeded at 25 °C.

The addition of 2-cyclohexenone (**1a**) to a THF solution of phenylrhodium complex **6** gave oxa-π-allylrhodium complex **9** as a single isomer (Scheme 8), whose ^{31}P NMR spectrum is shown as spectrum E in Figure 2. Two phosphorus atoms appeared as two dd's at 44.2 (J_{P-Rh} = 205 Hz, $J_{P-P,cis}$ = 51 Hz) and 54.8 ppm (J_{P-Rh} = 215 Hz, $J_{P-P,cis}$ = 51 Hz). Hydrolysis of oxa-π-allyl complex **9** with water produced (*S*)-3-phenylcyclohexanone (**3am**) of 99% ee together with hydroxo complex **8**, indicating that the addition of the phenyl−rhodium bond to the α,β-unsaturated ketone took place with nearly perfect enantioselectivity (99% ee). It follows that the stereochemical outcome in the catalytic reaction is determined at the enantioselective insertion step. It would be possible for the oxa-π-allyl complex to exist as a mixture of diastereoisomers (**9** and **9′**), which results from the coordination of diastereotopic faces of oxa-π-allyl, but actually only one species was observed in solution. It is probably due to the big difference in their thermodynamic stability,[21] isomer **9**, where rhodium is coordinated to oxa-π-allyl on the other side of phenyl, being much more stable than the other isomer. The reaction of [RhCl((*S*)-binap)]$_2$ (**4**) with 2 equiv of potassium enolates generated from (*S*)-3-phenylcyclohexanone (**3am**) (99% ee) and potassium hydride gave a mixture of three oxa-π-allylrhodium isomers (spectrum F in Figure 2), one of which is identical with that

(21) The diastereomeric isomers **9** and **9′** should exist in an equilibrium takes place by way of a rhodium enolate.

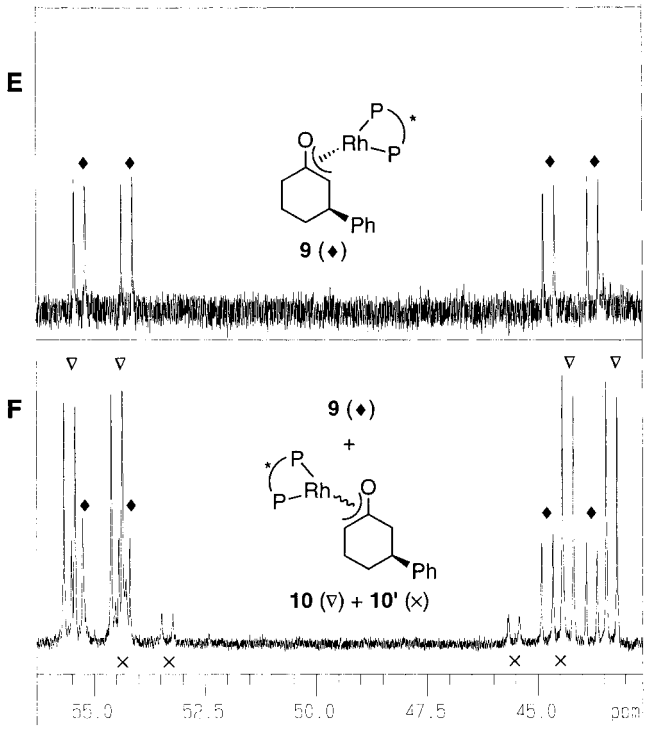
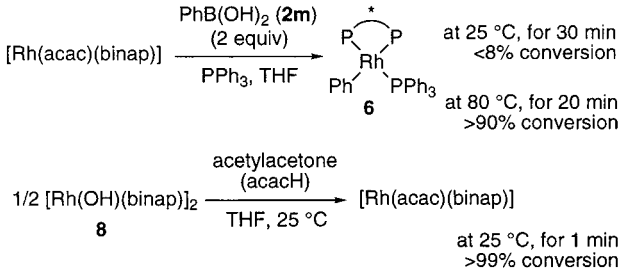


Figure 2. ^{31}P NMR spectra (at 202 MHz in THF at 25 °C) of oxa-π-allylrhodium complexes. (E) Reaction of phenylrhodium **6** with 2-cyclohexenone (**1a**) giving **9**. (F) A mixture of oxa-π-allylrhodium complexes **9** and **10** obtained by the reaction of [RhCl(binap)]$_2$ (**4**) with potassium enolates generated from (*S*)-**3am** and potassium hydride.

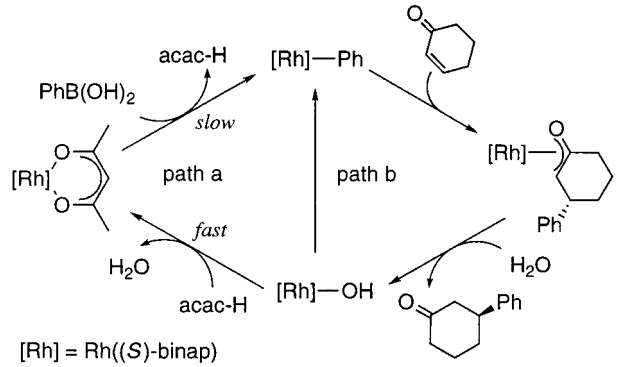
Scheme 9



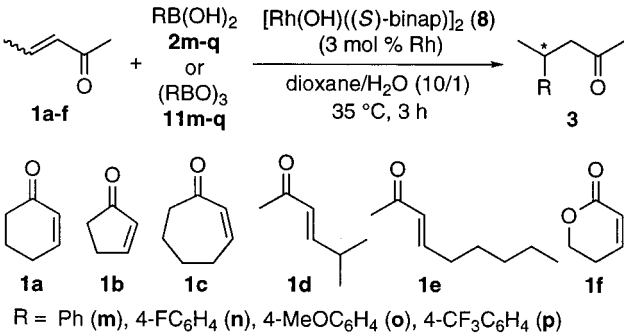
obtained from phenylrhodium complex **6** by the phenylrhodation of 2-cyclohexenone (**2m**). The other two isomers are considered to be regioisomeric oxa-π-allylrhodium complexes **10** and **10′** resulting from potassium enolate where the double bond is located at the other side of the phenyl group.

In the NMR experiments, it has been shown that each of the three steps in the catalytic cycle takes place at 25 °C. However, the catalytic reaction shown in Scheme 1 does not take place at 60 °C or lower. We found an answer to why the high temperature is required for the catalytic reaction. The transmetalation of the phenyl group from boronic acid **2m** is very slow at 25 °C for Rh(acac)(binap), which is the rhodium complex thus far used for the catalytic reaction (Scheme 9), while the transmetalation is fast at 25 °C for [Rh(OH)(binap)]$_2$ (cf. Scheme 7). For the transmetalation to Rh(acac)(binap) to proceed at a reasonable rate, a reaction temperature as high as 80 °C is required. It was also observed that the hydroxorhodium complex **8** is immediately converted into the Rh(acac)(binap) by addition of 1 equiv of acetylacetone. Thus, in the catalytic reaction starting with Rh complex whose anionic ligand is acetylacetonate, the transmetalation step is very slow and the hydroxorhodium species generated by hydrolysis of the oxa-

Scheme 10



Scheme 11



π-allyl complex is immediately converted into the acetylacetonate complex by reaction with acetylacetone generated at the transmetalation step (path a in Scheme 10).

The results obtained above during the studies on the catalytic cycle gave us an idea that the catalyst system which does not contain acetylacetonate should catalyze the asymmetric 1,4-addition at a lower temperature (path b in Scheme 10). It was actually successful. By use of the hydroxo complex [Rh(OH)(binap)]$_2$ (**8**) as a catalyst,[22] the catalytic 1,4-addition reaction proceeded even at 35 °C (Scheme 11). The results are summarized in Table 1, which also contains the data obtained with Rh(acac)(binap) as a catalyst for comparison. In the presence of 3 mol % of the hydroxorhodium catalyst **8** the 1,4-addition of phenylboronic acid (**2m**) or phenylboroxine[23] (**11m**) to 2-cyclohexenone (**1a**) took place at 35 °C to give a 96−98% yield of 1,4-addition product **3am** (entries 4, 5), while with the Rh(acac)(binap) catalyst the 1,4-addition is very slow at 60 °C or lower, almost no reaction taking place (entries 2 and 3). A hydroxorhodium complex generated in situ from [RhCl(binap)]$_2$ and potassium hydroxide[24] also catalyzed the 1,4-addition at 35 °C (entry 6). In addition to the lower reaction temperature, the new catalyst system has the following advantages over the rhodium acetylacetonate catalyst[8−10] thus far used. (1) The amount of boron reagent can be reduced while keeping the yield of 1,4-addition product high (entry 7). This is because hydrolysis of phenylboronic acid giving benzene, which is the main side reaction of the rhodium-catalyzed reaction,[8] is retarded by carrying out the reaction at a lower temperature. (2) The yield of 1,4-addition product is higher, especially for the addition of arylboronic acids whose hydrolysis is fast at the high temperature. A typical example is the addition of 4-methoxyphenylboron reagents. The reaction with [Rh(OH)(binap)]$_2$ (**8**) at 35 °C gave 96% yield of the 1,4-addition product, while no 1,4-addition is observed with the Rh(acac)(binap) catalyst at 100 °C (entries 10 and 11). For the introduction of the 4-fluorophenyl group, the yield is twice as high as that with the new hydroxo catalyst (entries 8 and 9). (3) Most importantly, the enantioselectivity is always higher in the reaction catalyzed by [Rh(OH)(binap)]$_2$ (**8**) than that catalyzed by the Rh(acac)(binap) catalyst, which results from the lower reaction temperature realized by use of the new catalyst system. All the reactions shown in Table 1 proceeded with higher enantioselectivity in the presence of [Rh(OH)(binap)]$_2$ (**8**) as a catalyst. It should be noted that the enantioselectivity is significantly lower with the rhodium catalyst generated in situ by mixing [Rh(OH)(cod)]$_2$ with binap ligand, because the exchange between cod and binap is not fast enough and [Rh(OH)(cod)]$_2$ possesses catalytic activity toward the 1,4-addition reaction.

Conclusions

We have succeeded in establishing the catalytic cycle of the rhodium-catalyzed asymmetric 1,4-addition reaction. All the intermediates and their transformations were observed in the NMR experiments using an actual catalyst system. This is a rare example of successful mechanistic studies where all the key steps were followed one by one and the catalytic cycle is completed. The catalytic cycle shown here, which involves insertion of an unsaturated compound into the aryl−rhodium bond followed by hydrolysis giving hydroarylation product and hydroxorhodium species, is also expected to be working in the rhodium-catalyzed addition reactions to some other multiple bonds such as the carbon−oxygen double bond[5] or the carbon−carbon triple bond,[4] which are carried out in an aqueous solvent. The study of the transmetalation step brought us a more catalytically active rhodium complex, [Rh(OH)(binap)]$_2$ (**8**), which catalyzes the asymmetric 1,4-addition reaction at a low temperature leading to higher yield of 1,4-addition product with higher enantioselectivity.

Experimental Section

General. All manipulations were carried out under a nitrogen atmosphere. Nitrogen gas was dried by passage through P_2O_5. NMR spectra were recorded on a JEOL JNM LA-500 spectrometer (500 MHz for ^{1}H, 125 MHz for ^{13}C, and 202 MHz for ^{31}P). Chemical shifts are reported in δ ppm referenced to an internal tetramethylsilane standard for ^{1}H NMR, chloroform-*d* (δ 77.0) for ^{13}C NMR, and external 85% H_3PO_4 standard for ^{31}P NMR.

Materials. Rhodium complexes [RhCl(C_2H_4)$_2$]$_2$[25] and [Rh(OH)(cod)]$_2$[19] were prepared according to the reported procedures. Phenylboronic acid (**2m**) was purchased from Tokyo Kasei Kogyo Co., Ltd. Other arylboronic acids[26] were prepared according to the reported procedures.

Preparation of [RhCl((*S*)-binap)]$_2$ (4). A solution of [RhCl(C_2H_4)$_2$]$_2$ (1.02 g, 2.62 mmol) and (*S*)-BINAP (3.42 g, 5.49 mmol) in CH_2Cl_2 (10 mL) was stirred at room temperture for 2 h. After concentration in vacuo the red-orange residue was tritulated in Et_2O (30 mL) and then the supernatant was removed by cannulation at 0 °C. The precipitate

(22) A hydroxorhodium complex, [Rh(OH)(cod)]$_2$ included in a cyclodextrin, has been reported to be an effective catalyst for the 1,4-addition in water: Itooka, R.; Iguchi, Y.; Miyaura, N. *Chem. Lett.* **2001**, 722.
(23) Concerning the use of arylboroxine in place of arylboronic acid for the rhodium-catalyzed 1,4-addition, see refs 9d and 9g.
(24) It has been reported that addition of KOH to a rhodium complex generates an active catalyst: Ramnauth, J.; Poulin, O.; Bratovanov, S. S.; Rakhit, S.; Maddafird, S. P. *Org. Lett.* **2001**, *3*, 2571.
(25) Cramer, R. *Inorg. Synth.* **1974**, *15*, 16.
(26) (a) Brown, H. C.; Cole, T. E. *Organometallics* **1983**, *2*, 1316. (b) Hawthorne, M. F. *J. Am. Chem. Soc.* **1958**, *80*, 4291.

Table 1. Asymmetric 1,4-Addition of Organoboron Reagents $RB(OH)_2$ (**2**) or $(RBO)_3$ (**11**) to α,β-Unsaturated Ketones and Esters **1** Catalyzed by [Rh(OH)((*S*)-binap)]$_2$ (**8**)[a]

entry	**1**	**2** or **11** (equiv[d] to **1**)	catalyst[b]	temp (°C)	time (h)	yield[c] (%) of **3**	% ee[e]
1[f]	**1a**	**2m** (2.5)	A	100	5	93 (**3am**)	97 (*S*)
2[f]	**1a**	**2m** (2.5)	A	60	5	3 (**3am**)	97 (*S*)
3[f]	**1a**	**2m** (2.5)	A	40	5	<2 (**3am**)	
4	**1a**	**2m** (2.5)	**8**	35	3	96 (**3am**)	99.3 (*S*)
5	**1a**	**11m** (2.5)	**8**	35	3	98 (**3am**)	99.3 (*S*)
6	**1a**	**2m** (2.5)	B	35	3	94 (**3am**)	99.1 (*S*)
7	**1a**	**11m** (1.4)	**8**	35	3	94 (**3am**)	99.2 (*S*)
8	**1a**	**2n** (2.5)	A	100	5	44 (**3an**)	97.6
9	**1a**	**11n** (2.5)	**8**	35	3	96 (**3an**)	99.1
10[g]	**1a**	**2o** (2.5)	A	100	5	0 (**3ao**)	
11	**1a**	**11o** (2.5)	**8**	35	3	96 (**3ao**)	99.1
12[f]	**1b**	**2m** (1.4)	A	100	5	93 (**3bm**)	97 (*S*)
13	**1b**	**11m** (2.5)	**8**	35	3	95 (**3bm**)	98 (*S*)
14[f]	**1c**	**2m** (1.4)	A	100	5	51 (**3 cm**)	93 (*S*)
15	**1c**	**11m** (2.5)	**8**	35	3	94 (**3 cm**)	96.3 (*S*)
16[f]	**1d**	**2m** (5.0)	A	100	5	82 (**3dm**)	97 (*S*)
17	**1d**	**11m** (2.5)	**8**	35	3	89 (**3dm**)	97.9 (*S*)
18[f]	**1e**	**2m** (2.5)	A	100	5	88 (**3em**)	92 (*R*)
19	**1e**	**11m** (2.5)	**8**	35	3	92 (**3em**)	97.8 (*R*)
20[h]	**1f**	**2p** (5.0)	A	100	5	75 (**3fp**)	97 (*S*)
21	**1f**	**11p** (2.5)	**8**	35	3	85 (**3fp**)	99.1 (*S*)

[a] The reaction was carried out with substrate **1** (0.40 mmol) in dioxane/H_2O (10/1, 2.2 mL) in the presence of 3 mol % of rhodium catalyst. [b] A: Rh(acac)((*S*)-binap) or the in situ generated catalyst from Rh(acac)$(C_2H_4)_2$ and (*S*)-binap. B: Catalyst generated in situ from [RhCl((*S*)-binap)]$_2$ and KOH. [c] Isolated yield by silica gel chromatography. [d] Equivalents of Ph-B unit to **1**. [e] Determined by HPLC analysis with chiral stationary phase columns: Daicel Chiralcel OD-H (hexane/2-propanol = 98/2) for **3am**, **3cm**, **3dm**, and **3em**; OB-H (hexane/2-propanol = 98/2) for **3bm**; AD (hexane/2-propanol = 9/1) for **3an** and **3ao**; and OG (hexane/2-propanol = 98/2) for **3fp**. [f] Reported in ref 8. [g] Reported in ref 9c. [h] Reported in ref 9b.

was washed five times with Et_2O at 0 °C and dried under vacuum. The yield of **4** was 3.92 g (98%). ^{1}H NMR (C_6D_6, 50 °C): δ 6.49 (br t, J = 7.3 Hz, 8H), 6.57 (t, J = 7.3 Hz, 4H), 6.66 (ddd, J = 8.6, 6.2 and 1.2 Hz, 4H), 6.69 (br d, J = 8.6 Hz, 4H), 6.97 (t, J = 7.3 Hz, 4H), 6.99 (ddd, J = 8.2, 6.2 and 1.6 Hz, 4H), 7.05 (t, J = 7.6 Hz, 8H), 7.20 (d, J = 8.7 Hz, 4H), 7.26 (d, J = 8.2 Hz, 4H), 7.60 (quint, J = 4.2 Hz, 4H), 8.01 (br, 8H), 8.28 (br, 8H); ^{31}P NMR (C_6D_6) δ 49.7 (d, J_{Rh-P} = 197 Hz). Anal. Calcd for $C_{88}H_{64}Cl_2P_4Rh_2$: C, 69.44; H, 4.24. Found: C, 69.16; H, 4.33.

Preparation of RhCl(PPh$_3$)((*S*)-binap) (5). A solution of **4** (846 mg, 0.556 mmol) and PPh_3 (350 mg, 1.33 mmol) in toluene (5 mL) was stirred at room temperature for 3 h. After concentration in vacuo the red residue was tritulated in Et_2O (10 mL) and then the supernatant was removed by cannulation at 0 °C. The precipitate was washed five times with Et_2O at 0 °C and dried under vacuum. The yield of **5** was 1.13 g (99%). ^{1}H NMR (C_6D_6, 50 °C) δ 6.21 (br, 2H), 6.35 (t, J = 6.9 Hz, 1H), 6.43−6.58 (m, 7H), 6.77−6.93 (m, 14H), 6.97 (t, J = 7.5 Hz, 1H), 7.19−7.31 (m, 7H), 7.67 (t, J = 7.3 Hz, 1H), 7.76 (m, 8H), 8.04 (br, 2H), 8.22−8.30 (m, 4H); ^{31}P NMR (C_6D_6) δ 29.6 (ddd, $J_{P-P,trans}$ = 375 Hz, J_{Rh-P} = 143 Hz, $J_{P-P,cis}$ = 36 Hz), 31.9 (ddd, $J_{P-P,trans}$ = 375 Hz, J_{Rh-P} = 144 Hz, $J_{P-P,cis}$ = 43 Hz), 50.6 (ddd, J_{Rh-P} = 185 Hz, $J_{P-P,cis}$ = 44 Hz, $J_{P-P,cis}$ = 36 Hz). Anal. Calcd for $C_{62}H_{47}ClP_3Rh$: C, 72.77; H, 4.63. Found: C, 72.95; H, 4.78.

Preparation of RhPh(PPh$_3$)((*S*)-binap) (6). The solid **5** (1.24 g, 1.12 mmol) was suspended in Et_2O (80 mL), and PhLi (2.2 mL, 0.88 M) was added at 0 °C. The mixture was stirred at room temperature for 72 h. After filtation of the insoluble LiCl, the solvent was removed in vacuo to yield dark-red powders. The powdery complex was dissolved in Et_2O (40 mL) and passed through a short alumina column (Et_2O) to give 946 mg (73%) of **6**. ^{1}H NMR (C_6D_6) δ 6.26−6.41 (m, 9H), 6.49−6.57 (m, 4H), 6.86−6.90 (m, 10H), 6.97−7.05 (m, 6H), 7.12 (t, J = 7.3 Hz, 1H), 7.19 (t, J = 7.3 Hz, 2H), 7.26 (d, J = 8.3 Hz, 1H), 7.31 (t, J = 7.8 Hz, 1H), 7.40−7.52 (m, 12H), 7.81−7.87 (m, 3H), 8.22 (t, J = 8.1 Hz, 2H), 8.43 (dd, J = 8.8 and 6.8 Hz, 1H); ^{31}P NMR (C_6D_6) δ 29.5 (ddd, $J_{P-P,trans}$ = 324 Hz, J_{Rh-P} = 178 Hz, $J_{P-P,cis}$ = 39 Hz), 32.8 (ddd, $J_{P-P,trans}$ = 324 Hz, J_{Rh-P} = 170 Hz, $J_{P-P,cis}$ = 30 Hz), 35.4 (ddd, J_{Rh-P} = 121 Hz, $J_{P-P,cis}$ = 39 Hz, $J_{P-P,cis}$ = 30 Hz). Anal. Calcd for $C_{68}H_{52}P_3Rh$: C, 76.69; H, 4.92. Found: C, 76.55; H, 5.22.

A Sequence of Reactions Starting with Phenylrhodium Complex 6 in an NMR Sample Tube. Conversion into Oxa-π-allylrhodium Complexes 7 and 7′, Hydroxorhodium Complex 8, and Phenylrhodium Complex 6. The ^{31}P NMR charts obtained are shown in Figure 1. In an NMR sample tube a solution of **6** (26.6 mg, 25.0 μmol) in THF (0.5 mL) was charged and 4,4-dimethyl-1-penten-3-one (14.0 mg, 125 μmol) was added at 25 °C. After 1 h, the ^{31}P NMR spectrum of the solution showed generation of free PPh_3 (−4.5 ppm) and two diastereomeric isomers of oxa-π-allylrhodium species **7** and **7′** in a ratio of 2:1. **7**: ^{31}P NMR (THF) δ 37.9 (dd, J_{Rh-P} = 186 Hz, J_{P-P} = 45 Hz), 48.4 (dd, J_{Rh-P} = 222 Hz, J_{P-P} = 45 Hz). **7′**: ^{31}P NMR (THF) δ 40.8 (dd, J_{Rh-P} = 182 Hz, J_{P-P} = 45 Hz), 49.5 (dd, J_{Rh-P} = 228 Hz, J_{P-P} = 45 Hz). To the solution containing oxa-π-allylrhodium **7** and **7′** was added water (5 μL). In 10 min all the rhodium complexes were completely converted into [Rh(OH)((*S*)-binap)]$_2$ (**8**). Free PPh_3 remained at −4.5 ppm. **8**: ^{31}P NMR (THF) δ 55.0 (d, J_{Rh-P} = 186 Hz). To the reaction mixture was added a solution of phenylboronic acid (30.5 mg, 250 μmol) in THF (0.1 mL). In 1 h, most of the **8** was replaced by the phenylrhodium complex **6**.

Reaction of [RhCl((*S*)-binap)]$_2$ (4) with Potassium Enolate of 4,4-Dimethyl-1-phenylpenten-3-one Forming Oxa-π-allylrhodium Complexes 7 and 7′. In an NMR sample tube, **4** (22.8 mg, 15.0 μmol) and a powdery potassium enolate (6.9 mg, 30.0 μmol) prepared from 4,4-dimethyl-1-phenylpentan-3-one and potassium hydride were charged and THF (0.5 mL) was added at 25 °C. Within 40 min, **4** was completely converted into a 2:1 mixture of **7** and **7′**. **7**: ^{1}H NMR (C_6D_6) δ 1.30 (s, 9H), 3.40 (br d, J = 12.7 Hz, 1H), 3.49 (br d, J = 11.3 Hz, 1H), 4.02 (dd, J = 12.7 and 11.3 Hz, 1H); ^{31}P NMR (THF) δ 37.9 (dd, J_{Rh-P} = 185 Hz, J_{P-P} = 44 Hz), 48.3 (dd, J_{Rh-P} = 222 Hz, J_{P-P} = 44 Hz). **7′**: ^{1}H NMR (C_6D_6) δ 1.32 (s, 9H), 2.48 (br d, J = 12.5 Hz, 1H), 3.63 (br d, J = 10.6 Hz, 1H), 3.69 (br dd, J = 12.5 and 10.6 Hz, 1H); ^{31}P NMR (THF) δ 40.8 (dd, J_{Rh-P} = 182 Hz, J_{P-P} = 44 Hz), 49.4 (dd, J_{Rh-P} = 222 Hz, J_{P-P} = 44 Hz).

Reaction of Phenylrhodium Complex 6 with 2-Cyclohexen-1-one (1a) Forming Oxa-π-allylrhodium Complex 9. In an NMR sample tube, 2-cyclohexen-1-one (19.2 mg, 200 μmol) was added to a solution of **6** (21.3 mg, 20.0 μmol) in THF (0.5 mL). The ^{31}P NMR spectrum of the solution showed generation of free PPh_3 (−4.5 ppm) and oxa-π-allylrhodium complex **9**. After 2 h, 17% of **6** was converted into **9**.

9: ^{31}P NMR (THF) δ 44.2 (dd, J_{Rh-P} = 205 Hz, J_{P-P} = 51 Hz), 54.8 (dd, J_{Rh-P} = 215 Hz, J_{P-P} = 51 Hz).

Reaction of [RhCl((*S*)-binap)]$_2$ (4) with Potassium Enolate of (*S*)-3-Phenylcyclohexan-1-one Forming Oxa-π-allylrhodium Complexes 9 and 10. A mixture of **4** (304 mg, 0.200 mmol) and a powdery potassium enolate (85 mg, 0.40 mmol) generated from (*S*)-3-phenylcyclohexan-1-one and potassium hydride in THF (3 mL) was stirred at 25 °C for 1 h. ^{31}P NMR of the mixture showed that **4** was completely converted into oxa-π-allylrhodium complexes which can be assigned to regio- and diastereoisomers **9**, **10**, and **10′** in a ratio of 2:8:1. **9**: ^{31}P NMR (THF) δ 44.3 (dd, J_{Rh-P} = 205 Hz, J_{P-P} = 51 Hz), 54.8 (dd, J_{Rh-P} = 215 Hz, J_{P-P} = 51 Hz). **10**: ^{31}P NMR (THF) δ 43.8 (dd, J_{Rh-P} = 202 Hz, J_{P-P} = 50 Hz), 55.0 (dd, J_{Rh-P} = 216 Hz, J_{P-P} = 50 Hz). **10′**: ^{31}P NMR (THF) δ 45.0 (dd, J_{Rh-P} = 205 Hz, J_{P-P} = 51 Hz), 53.9 (dd, J_{Rh-P} = 212 Hz, J_{P-P} = 51 Hz).

Reaction of [Rh(OH)(cod)]$_2$ with (*S*)-binap Forming [Rh(OH)((*S*)-binap)]$_2$ (8). A solution of [Rh(OH)(cod)]$_2$ (68.4 mg, 0.150 mmol) and (*S*)-binap (187 mg, 0.300 mmol) in benzene (3 mL) was stirred at 50 °C for 2 h. The dark-red solution was filtered through Celite using 10 mL of benzene, and the filtrate was concentrated in volume into ca. 3 mL. EtOH (10 mL) was added, and the mixture was left for 6 h until a considerable amount of dark-red crystals were precipitated. The crystals were separated, washed with EtOH (4 × 5 mL), and dried under vacuum. The yield of **8** was 152 mg (68%). Mp 212−214 °C dec. ^{1}H NMR (C_6D_6) δ −1.90 (s, 2H), 6.57 (br, 8H), 6.59 (t, J = 6.7 Hz, 4H), 6.63 (d, J = 3.4 Hz, 8H), 6.70 (t, J = 7.2 Hz, 4H), 6.76 (t, J = 7.3 Hz, 8H), 6.98 (ddd, J = 8.1, 4.2, and 3.1 Hz, 4H), 7.14 (d, J = 8.8 Hz, 4H), 7.23 (d, J = 8.3 Hz, 4H), 7.44 (quint, J = 4.2 Hz, 4H), 8.14 (br, 8H), 8.30 (very br, 8H); ^{31}P NMR (C_6D_6) δ 55.2 (d, J_{Rh-P} = 185 Hz). This complex is extremely air sensitive, and satisfactory elemental analysis could not be achieved.

Preparation of [Rh(OH)((*S*)-binap)]$_2$ (8) from [RhCl((*S*)-binap)]$_2$ (4). Aqueous KOH (0.6 mL, 5 M) was added to a solution of **4** (228.3 mg, 0.150 mmol) in THF (6 mL). The solution was stirred at room temperature for 30 min and then concentrated in vacuo. The crude mixture was dissolved in benzene (5 mL), and the organic layer was washed with water (2 × 5 mL). The organic layer was dried over anhydrous Na_2SO_4 and concentrated. The residual solid was dried under vacuum. The yield of **8** was 132 mg (60%). Complex **8** thus obtained was used as a catalyst without further purification for the asymmetric 1,4-addition reaction.

Rhodium-Catalyzed 1,4-Addition. The reaction conditions and results are summarized in Table 1. A typical procedure is given for the reaction of 2-cyclohexen-1-one (**1a**) with phenylboroxine (**11m**) giving (*S*)-3-phenylcyclohexan-1-one (**3am**) (entry 5): To a mixture of [Rh(OH)((*S*)-binap)]$_2$ (**8**) (8.9 mg, 6 μmol) and phenylboroxine (104 mg, 0.33 mmol) were added 1,4-dioxane (2 mL), water (0.2 mL), and 2-cyclohexen-1-one (39 mg, 0.40 mmol). The mixture was stirred at 35 °C for 3 h. After evaporation of the solvent, the residue was dissolved in ethyl acetate. The solution was washed twice with saturated aqueous sodium bicarbonate and dried over anhydrous magnesium sulfate. Chromatography on silica gel (hexane:EtOAc 4:1) gave (*S*)-3-phenylcyclohexan-1-one (68 mg, 98%) as a colorless oil.

3an: ^{1}H NMR ($CDCl_3$) δ 1.73−1.86 (m, 2H), 2.07 (dm, J = 11.6 Hz, 1H), 2.12−2.17 (m, 1H), 2.38 (td, J = 12.7 and 6.3 Hz, 1H), 2.45−2.51 (m, 2H), 2.58 (ddt, J = 13.9, 4.1, and 2.1 Hz, 1H), 3.00 (tt, J = 11.8 and 3.9 Hz, 1H), 7.01 (t, J = 8.6 Hz, 2H), 7.18 (dd, J = 8.6 and 5.5 Hz, 2H); ^{13}C NMR ($CDCl_3$) δ 25.37, 32.85, 41.08, 43.96, 49.05, 115.40 (d, $^2J_{C-F}$ = 21.0 Hz), 127.95 (d, $^3J_{C-F}$ = 8.3 Hz), 140.00 (d, $^4J_{C-F}$ = 3.1 Hz), 161.49 (d, $^1J_{C-F}$ = 244 Hz), 210.69. Anal. Calcd for $C_{12}H_{13}OF$: C, 74.98; H, 6.82. Found: C, 74.88; H, 6.87. $[\alpha]^{20}_D$ −18.7 (*c* 1.00, $CHCl_3$) for (*S*)-**3an** of 99.1% ee.

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