# Synthesis of Novel Chiral Benzophospholanes and Their Application in Asymmetric Hydrogenation

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Dedicated to Professor Ryoji Noyori on the occasion of his receiving a Nobel Prize

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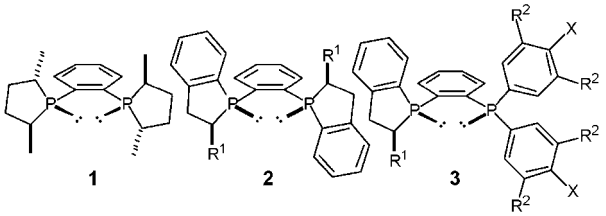
**Abstract:** A new class of chiral ligands bearing one or two benzophospholanes was developed for the purpose of Ru-catalyzed asymmetric hydrogenation. Although results of the Ru catalysis remain insufficient so far, 1,2-bis(2-isopropyl-2,3-dihydro-1*H*-phosphindol-1-yl)benzene (iPr-BeePHOS: **2b**) has been found to provide high enantioselectivity in the Rh-catalyzed asymmetric hydrogenation of an enamide.

**Keywords:** asymmetric catalysis; homogeneous catalysis; hydrogenation; P-ligands; rhodium

Catalytic asymmetric hydrogenation of prochiral unsaturated compounds is considered to be one of the most powerful tools in asymmetric syntheses.[1] The perfect harmony of a central metal and a chiral ligand enables high asymmetric control. In particular, the key to success is the invention and synthesis of metal complexes which contain efficient ligands. Since the first report of asymmetric hydrogenation by Kagan,[2] a number of chiral ligands, especially diphosphine ligands, have been reported.[1a] The invention of the excellent ligands such as DIPAMP[3] and BINAP[4] is among the important milestones in this research. Recently another monumental work was accomplished by Burk and coworkers, who developed DuPHOS[5] (**1**) which has an excellent stereorecognition ability in asymmetric hydrogenations. The high enantioselectivity is often explained by a rigid 1,2-phenylene backbone and electron-rich phospholane groups. Prompted by this study, many researchers have utilized the ligand as a model for new ones, affording successful ligands such as PennPHOS,[6] BINAPHANE,[7] R-CnrPHOS,[8] RoPHOS[9] and BASPHOS.[10]

We thought that the high enantioselectivity in asymmetric hydrogenation using DuPHOS might be a result of the proper location of the enantiodetermining alkyl group which lies axially on the phospholane ring. Then, we came to think that the excellent stereorecognition ability of DuPHOS could be applied to Ru-catalyzed hydrogenations, since the usage of Ru is advantageous for chemical industries. Among possible indispensable factors for Ru catalysis, we focused on the number of aryl groups on the phosphorus atom, as many diphosphine ligands which have two or more aryl groups on each phosphine such as BINAP succeed in Ru catalysis with high enantioselectivity. This fact drove us to the working hypothesis that ligands with more aromatic groups on phosphorus atoms might give more catalytic activity for Ru catalysis. In designing new ligands, we tried to utilize the DuPHOS's proper location of the enantiodetermining group with more aryl groups on the phosphorus atoms. Some of the candidates are new diphosphine ligands bearing benzophospholane, that is, 1,2-bis(2-alkyl-2,3-dihydro-1*H*-phosphindol-1-yl)benzenes (**2**), which are called BeePHOSes. These diphosphine ligands have two aryl group on each phosphorus atom and we expected that these ligands might realize Ru catalysis as well as Rh catalysis.

Described herein is the preparation of BeePHOSes **2**, as well as $C_1$-symmetric mBeePHOSes **3** which have more aryl groups. Their application to Ru- and Rh-catalyzed asymmetric hydrogenation is also described.




**2a**: BeePHOS ; $R^1$ = Me
**2b**: iPr-BeePHOS ; $R^1$ = *i*-Pr
**3a**: mBeePHOS-Ph ; $R^1$ = Me, $R^2$ = X = H
**3b**: iPr-mBeePHOS-Ph ; $R^1$ = *i*-Pr, $R^2$ = X = H
**3c**: iPr-mBeePHOS-DTBM; $R^1$ = *i*-Pr, $R^2$ = *t*-Bu, X = OMe

**Figure 1.** Structures of ligands **1**, **2** and **3**.

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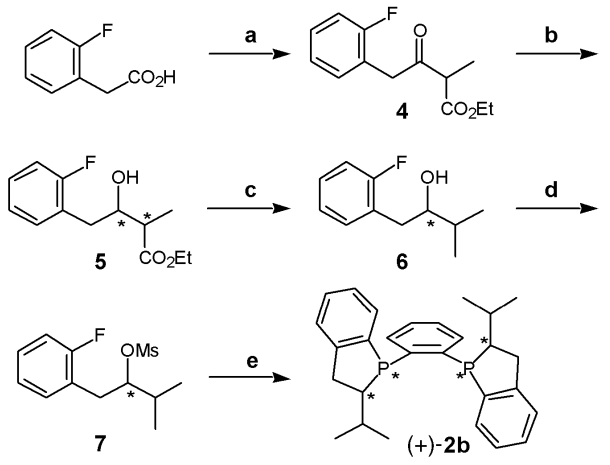
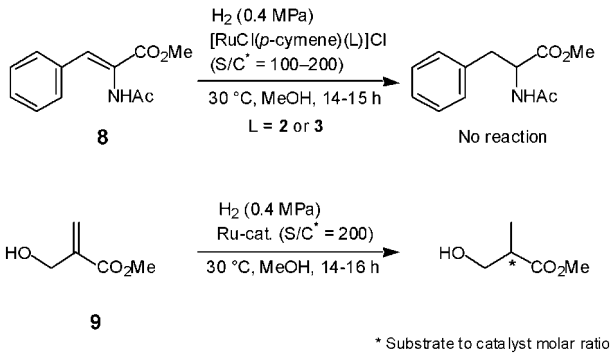



a: i)CDI, ii) $MgCl_2$, $MeCH(CO_2Et)(CO_2K)$
b: $H_2$, $[\{RuCl((R)\text{-segphos})\}_2(\mu\text{-}Cl)_3][Me_2NH_2]$
c: i) $LiAlH_4$, ii) TsCl, $Et_3N$, iii) $LiAlH_4$
d: MsCl, $Et_3N$
e: i) 1,2-$C_6H_4(PHLi)_2$, ii) *n*-BuLi

**Scheme 1.** Synthesis of (+)-iPr-BeePHOS.




**Scheme 2.** Ru-catalyzed asymmetric hydrogenation.

The synthesis of **2b** is shown in Scheme 1. Exposure of 2-fluorophenylacetic acid and 1,1′-carbonylbis-1*H*-imidazole (CDI) followed by treatment with ethyl potassium methylmalonate in the presence of magnesium chloride afforded the corresponding β-ketoester **4**. Asymmetric hydrogenation of **4** using the Ru-SEGPHOS complex[11] gave β-hydroxyester **5.** Subsequent conversion of an ester moiety into a methyl group led to the alcohol **6.** The mesylate **7** derived from **6** was then treated with 1,2-bis(phosphino)benzene[12] in the presence of *n*-BuLi to afford **2b** as a single diastereoisomer. On the other hand, **2a** was synthesized from the mesylate which was prepared using an asymmetric lithiation-methylation process of the corresponding carbamate followed by deprotection[13] and mesylation. Compounds **3a**, **3b** and **3c** were prepared analogously using the corresponding 2-(diarylphosphino)phenylphosphines.[14]

Absolute configurations at the phosphorus atom and the C-2 position of phospholane remain unknown so far. Mechanistic studies could indicate the desired diastereomer as described in Figure 1 although the possibility of the other diastereomer cannot be excluded completely.

Trials of the Ru-catalyzed asymmetric hydrogenation were performed. The reaction rarely proceeded under the conditions described in Scheme 2 when methyl *N*-acetamidocinnamate (**8**) was used as a substrate, whereas methyl α-hydroxymethylacrylate (**9**) was hydrogenated in some cases. The results of the Ru-catalyzed asymmetric hydrogenation of **9** are described in Table 1. Disappointingly, enantioselectivities were extremely low in all cases. Although conversions were also unsatisfactory, conversions of Ru complexes bearing mBeePHOS were higher than those bearing BeePHOS (entry 1 *vs.* 2, 3 *vs.* 4, 6 *vs.* 7). This fact supports our working hypothesis that phosphine ligands with more aryl groups should give greater hydrogenation ability to the Ru complexes.

Next, Rh complexes of **2** and **3** were applied to the asymmetric hydrogenation of **8** and **9**. The reactions were performed using cationic Rh complexes as catalyst precursors. Contrary to our expectation that **2b** should have the same asymmetric environment as **1**, in the asymmetric hydrogenation of **8**, the use of BeePHOS

**Table 1.** Ru-catalyzed asymmetric hydrogenation of **9**.[a]

| Entry | Ru catalyst | Conversion[b] [%] | % ee[b](config.)[c] |
|---|---|---|---|
| 1 | [RuCl(*p*-cymene)((+)-**2a**)]Cl | trace | – |
| 2 | [RuCl(*p*-cymene)((+)-**3a**)]Cl | 96 | 1 (*R*) |
| 3 | [RuCl(*p*-cymene)((+)-**2b**)]Cl | 0 | – |
| 4 | [RuCl(*p*-cymene)((+)-**3b**)]Cl | 3 | 4 (*S*) |
| 5 | [RuCl(*p*-cymene)((*R,R*)-**1**)]Cl | trace | – |
| 6 | $Ru(OAc)_2$((+)-**2b**) | 30 | 9 (*R*) |
| 7 | $Ru(OAc)_2$((+)-**3b**) | 78 | 16 (*R*) |

[a] Reactions were carried out using Ru-catalyst (S/C = 200) under an initial hydrogen pressure of 0.4 MPa at 30 °C in methanol for 14 – 16 h.
[b] Conversion and ee were determined by GC (Cp Chirasil DEX-CB).
[c] Absolute configuration was confirmed by comparison of GC elution order with configurationally defined examples.

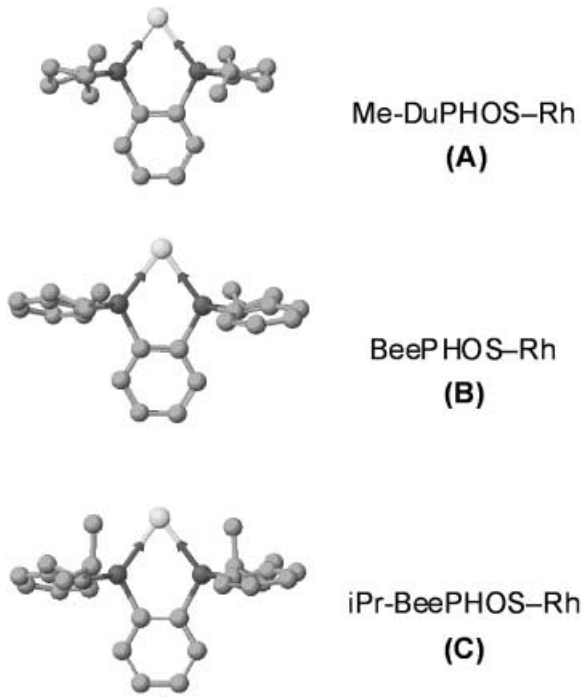



**Figure 2.**

(**2a**) as the ligand afforded methyl *N*-acetylphenylalanine in only 59% ee (entry 1), whereas Me-DuPHOS (**1**) afforded 98% ee (entry 6). iPr-BeePHOS (**2b**), however, gave the hydrogenated product in as high as 98% ee (entry 2). This result can be explained by computational studies. The calculated structure of the Rh complexes bearing Me-DuPHOS (**1**) (**A**), BeePHOS (**2a**) (**B**) and iPr-BeePHOS (**2b**) (**C**) (CAChe MM2 calculations) are shown in Figure 2. The phospholane ring of BeePHOS (**2a**) is distorted by the benzo moiety, making the attached methyl group pseudo-equatorial (**B**). This conformation decreased the protrusion of the enantiodetermining methyl group over the Rh metal, causing lower enantioselectivity. In the case of iPr-BeePHOS (**2b**), although the *i*-Pr groups themselves are also located pseudo-equatorially, the β-methyl moiety is located pseudo-axially (**C**), which could compensate for the deficiency of protrusion and realize enantioselectivity as high as Me-DuPHOS.

mBeePHOSes yielded lower ee, having the same tendency as BeePHOS, whereas the reaction did not proceed when **3c** was used (entries 3–5). In the asymmetric hydrogenation of **9**, *i*-Pr-type ligands afforded higher ees than their Me-counterparts (entry 7 *vs.* 8, 9 *vs.* 10). Rh complexes with mBeePHOS, in turn, gave higher ees than those with BeePHOS (entry 7 *vs.* 9, 8 *vs.* 10) although the enantioselectivities were not as high as that of Me-DuPHOS. Steric hindrance on **3** seemed not to have much influence on enantioselectivity in this hydrogenation (entry 10 *vs.* 11).

In conclusion, new chiral diphosphine ligands, BeePHOS and mBeePHOS, were developed. Although the enantioselectivities of the Ru-catalyzed asymmetric hydrogenation were disappointing, they might suggest the necessity of aryl groups on the phosphorus atom for Ru catalysis. In the Rh catalysts, however, the complex bearing iPr-BeePHOS has been found to hydrogenate an enamide in high enantioselectivity. Application to other asymmetric hydrogenations using these ligands is in progress. Determination of the stereochemistry of the ligand is being investigated.

**Table 2.** Rh-catalyzed asymmetric hydrogenation of **8** and **9**.[a]

| Entry | Substrate | Ligand (L) | Conversion[b] [%] | % ee[b] (config.)[c] |
|---|---|---|---|---|
| 1 | **8** | (+)-**2a** | >99 | 59 (*R*) |
| 2 | **8** | (+)-**2b** | >99 | 98 (*R*) |
| 3 | **8** | (+)-**3a** | >99 | 47 (*R*) |
| 4 | **8** | (+)-**3b** | >99 | 73 (*R*) |
| 5 | **8** | (+)-**3c** | trace | – |
| 6[d] | **8** | (*R,R*)-**1** | >99 | 98 (*R*) |
| 7 | **9** | (+)-**2a** | 58 | 7 (*S*) |
| 8 | **9** | (+)-**2b** | >99 | 56 (*S*) |
| 9 | **9** | (+)-**3a** | >99 | 46 (*S*) |
| 10 | **9** | (+)-**3b** | >99 | 66 (*S*) |
| 11 | **9** | (+)-**3c** | >99 | 51 (*S*) |
| 12 | **9** | (*R,R*)-**1** | >99 | 90 (*S*) |

[a] Reactions were carried out using [Rh(cod)(L)]OTf (S/C = 200) as a catalyst precursor under an initial hydrogen pressure of 0.4 MPa at 30 °C in methanol for 14 – 16 h.
[b] Conversion and ee were determined by HPLC (Daicel CHIRALCEL OJ: methyl *N*-acetylphenylalanine) and GC (Cp Chirasil DEX-CB: methyl 3-hydroxyisobutyrate).
[c] Absolute configurations were confirmed by comparison of chiral HPLC and GC elution order with configurationally defined examples.
[d] Our result: an initial hydrogen pressure of 0.2 MPa.

## Experimental Section

### Ethyl 4-(2-Fluorophenyl)-2-methyl-3-oxobutyrate (4)

1,1′-Carbonylbis-1*H*-imidazole (23.0 g, 142 mmol) was added to a solution of 2-fluorophenylacetic acid (20.0 g, 129 mmol) in acetonitrile (30 mL) at room temperature. After stirring for 1 h, the resultant solution was added to a mixture of ethyl potassium methylmalonate (33.3 g, 181 mmol), magnesium chloride (14.7 g, 155 mmol) and acetonitrile (60 mL). The mixture was stirred overnight at 45 °C, then treated with 1 N HCl (200 mL) and extracted 3 times with ethyl acetate (200 mL). The combined organic layer was washed with 1 N HCl, 5% sodium carbonate solution, water and brine and then dried over $Na_2SO_4$ followed by evaporation under vacuum. Purification of the residue using silica gel column chromatography gave **4**; yield: 23.1 g (95%). $^1$H NMR ($CDCl_3$): δ = 1.27 (3H, t, *J* = 7.2 Hz), 1.36 (3H, d, *J* = 7.2 Hz), 3.64 (1H, q, *J* =

7.2 Hz), 3.88 (2H, s), 4.18 (2H, q, $J = 7.2$ Hz), 6.95 – 7.15 (4H, m); EI-MS: $m/z = 238$ $(M)^+$.

### Ethyl 4-(2-Fluorophenyl)-3-hydroxy-2-methylbutyrate (5)

A 500 mL stainless steel autoclave was charged under a nitrogen stream with $[\{RuCl((R)\text{-segphos})\}_2(\mu\text{-}Cl)_3][Me_2NH_2]$ (138 mg, 0.084 mmol), **4** (20 g, 83.9 mmol) and ethanol (80 mL). Hydrogen (3.0 MPa) was introduced and the mixture was stirred for 18 h at 80 °C. Evaporation under vacuum and purification by silica gel chromatography gave **5** as a diastereomeric mixture (*ca.* 1:1); yield: 18.6 g (93%). The optical purity of the two diastereomers was 96.9% ee and 98.5% ee, respectively. The optical purity was determined by GC analysis (Cp Chirasil DEX-CB). EI-MS: $m/z = 241$ $(M + 1)^+$.

### 4-(2-Fluorophenyl)-2-methylbutane-1,3-diol

A solution of **5** (18.0 g, 74.9 mmol) in THF (180 mL) was added to a suspension of lithium aluminum hydride (2.84 g, 74.9 mmol) in THF (30 mL). The reaction mixture was stirred for 18 h at room temperature, and water (5 mL) and 1 N NaOH (5 mL) were added. Filtration, evaporation under vacuum and purification by silica gel chromatography gave the product; yield: 14.5 g (99%). EI-MS: $m/z = 199$ $(M + 1)^+$.

### 4-(2-Fluorophenyl)-3-hydroxy-2-methylbutyl *p*-Toluenesulfonate

4-(2-Fluorophenyl)-2-methylbutane-1,3-diol (13.5 g, 68.1 mmol), triethylamine (14.2 mL, 21.3 mmol), dichloromethane (70 mL) was cooled to 0 °C and *p*-toluenesulfonyl chloride (13.0 g, 68.1 mmol) was added. After stirring overnight at room temperature, the reaction mixture was treated with water and extracted 3 times with dichloromethane. The combined extract was dried over $Na_2SO_4$ and evaporated under vacuum. Purification of the residue by silica gel column chromatography gave the product; yield: 21.1 g (88%). EI-MS: $m/z = 353$ $(M + 1)^+$.

### (+)-1-(2-Fluorophenyl)-3-methylbutan-2-ol [(+)-6]

A solution of 4-(2-fluorophenyl)-3-hydroxy-2-methylbutyl *p*-toluenesulfonate (21.1 g, 60.2 mmol) in THF (210 mL) was added into a suspension of lithium aluminum hydride (2.28 g, 60.2 mmol) in THF (25 mL) at room temperature. The reaction mixture was stirred for 30 min, followed by the addition of $Na_2SO_4 \cdot 10\ H_2O$. Filtration, evaporation under vacuum and purification by silica gel chromatography gave (+)-**6**; yield: 9.6 g (88%, 98.1% ee). The ee was determined by GC analysis (Cp Chirasil DEX-CB); mp 37 – 38 °C; $[\alpha]_D^{24}$: + 27.9 (*c* 1.0, $CHCl_3$); $^1H$ NMR ($CDCl_3$): $\delta = 1.01$ (6H, d, $J = 6.6$ Hz), 1.76 (1H, dqq, $J = 5.5$, 6.6, 6.6 Hz), 2.63 (1H, dd, $J = 9.63$, 13.2 Hz), 2.92 (1H, dd, $J = 2.7$, 13.2 Hz), 3.64 (1H, m), 7.00 – 7.10 (2H, m), 7.18 – 7.28 (2H, m); EI-MS: $m/z = 182$ $(M)^+$.

### (+)-1-(2-Fluorobenzyl)-2-methylpropyl Methanesulfonate [(+)-7]

A mixture of **6** (8.6 g, 47.2 mmol), triethylamine (7.9 mL, 56.6 mmol) and dichloromethane (40 mL) was cooled to 0 °C, and then methanesulfonyl chloride (4.0 mL, 51.9 mmol) was added to the mixture. The reaction mixture was stirred overnight at room temperature, then treated with water and extracted 3 times with dichloromethane. The combined extract was washed with brine, dried over $Na_2SO_4$ and evaporated under vacuum. Purification by silica gel column chromatography gave (+)-**7**; yield: 12.5 g (91%); $[\alpha]_D^{24}$: + 30.8 (*c* 1.0, $CHCl_3$); $^1H$ NMR ($CDCl_3$): $\delta = 1.06$ (3H, d, $J = 7.0$ Hz), 1.08 (3H, d, $J = 7.0$ Hz), 2.07 (1H, dqq, $J = 4.2$, 7.0, 7.0 Hz), 2.48 (3H, s), 2.93 (1H, dd, $J = 9.0$, 14.6 Hz), 3.06 (1H, dd, $J = 4.4$, 14.6 Hz), 4.77 (1H, ddd, $J = 4.2$, 4.4, 9.0 Hz), 6.98 – 7.15 (2H, m), 7.18 – 7.32 (2H, m).

### (+)-1,2-Bis(2-isopropyl-2,3-dihydro-1*H*-phosphindol-1-yl)benzene [(+)-iPr-BeePHOS] [(+)-2b]

1,2-Bis(phosphino)benzene (300 μL, 2.32 mmol) in THF (9 mL) was cooled to 0 °C and 1.6 M *n*-butyllithium in hexane (2.9 mL, 4.64 mmol) was added dropwise. After stirring for 1 h at 0 °C, a solution of (+)-**7** (1.21 g, 4.64 mmol) in THF (12 mL) was added. The reaction mixture was stirred for 1 h at 0 °C and then for 1 h at room temperature. The mixture was cooled to 0 °C and 1.6 M *n*-butyllithium in hexane (4.4 mL, 6.96 mmol) was added. Subsequently it was stirred overnight at room temperature. The reaction mixture was treated with water (1 mL) and evaporated under vacuum. The residue was then treated with water and extracted 3 times with diethyl ether. The combined extract was washed with water and evaporated under vacuum. Purification by silica gel column chromatography gave (+)-**2b**; yield: 227 mg (23%); mp 70 – 71 °C; $[\alpha]_D^{24}$: + 186.1 (*c* 1.0, $CHCl_3$); $^1H$ NMR ($CDCl_3$): $\delta = 1.05$ (6H, d, $J = 6.4$ Hz), 1.09 (6H, d, $J = 6.8$ Hz), 2.09 – 2.21 (2H, m), 2.60 – 2.69 (2H, m), 2.93 – 3.01 (2H, m), 3.28 – 3.36 (2H, m), 6.74 – 6.80 (2H, m), 7.02 – 7.06 (2H, m), 7.18 – 7.40 (8H, m); $^{31}P$ NMR ($CDCl_3$): $\delta = 0.27$ (s); HRMS: calcd. for $C_{28}H_{32}P_2$: 430.1978; found: 430.1960.

### [Rh(cod)((+)-ipr-beephos)]OTf

A solution of (+)-**2b** (50.0 mg, 0.116 mmol) in dichloromethane (2.5 mL) was added dropwise to a solution of $[Rh(cod)_2]OTf$ (54.3 mg, 0.116 mmol) in dichloromethane (5 mL). After stirring overnight at room temperature, the solvent was removed under vacuum. The residue was dissolved with dichloromethane (0.5 mL), and diethyl ether (5 mL) was slowly added, yielding an orange precipitate. The solution was then removed and the solid was washed twice with diethyl ether and dried under vacuum to afford the product; yield: 73.8 mg (81%); $^1H$ NMR ($CD_2Cl_2$): $\delta = 1.18$ (6H, d, $J = 6.6$ Hz), 1.22 (6H, d, $J = 6.6$ Hz), 2.17 – 2.36 (8H, m), 2.47 – 2.55 (2H, m), 2.88 – 2.99 (2H, m), 3.11 – 3.17 (2H, m), 3.68 – 3.78 (2H, m), 5.03 – 5.10 (2H, m), 5.14 – 5.20 (2H, m), 7.11 – 7.15 (2H, m), 7.32 – 7.41 (4H, m), 7.47 – 7.54 (4H, m), 7.58 – 7.63 (2H, m); $^{31}P$ NMR ($CD_2Cl_2$): $\delta = 73.4$ (d, $J = 151.5$ Hz).

### Asymmetric Hydrogenation of Methyl *N*-Acetamidocinnamate (8)

[Rh(cod)((+)-ipr-beephos)]OTf (2.3 mg, 0.0029 mmol), methyl *N*-acetamidocinnamate (125 mg, 0.570 mmol) and methanol (1.5 mL) were charged into a 100 mL stainless steel autoclave under a nitrogen stream. Hydrogen (0.4 MPa) was introduced and the mixture was stirred for 14 h at 30 °C. The conversion and ee of methyl *N*-acetylphenylalanine were determined by HPLC analysis (Daicel CHIRALCEL OJ ; > 99% conversion, 98% ee).

## References


[1] For reviews, see: a) K. Takaya, T. Ohta, R. Noyori, in *Catalytic Asymmetric Synthesis*, (Ed.: I. Ojima), VCH: Weinheim, **1993**, Chapter 1, p. 1; 1b) R. Noyori, in *Asymmetric Catalysis in Organic Synthesis*, Wiley: New York, **1994**, p. 16.

[2] H. B. Kagan, T.-P. Dang, *J. Am. Chem. Soc.* **1972**, *94*, 6429 – 6433.

[3] a) W. S. Knowles, M. J. Sabacky, B. D. Vineyard, D. J. Weinkauff, *J. Am. Chem. Soc.* **1975**, *97*, 2567 – 2568; b) W. S. Knowles, *Acc. Chem. Res.* **1983**, *16*, 106 – 112.

[4] a) A. Miyashita, A. Yasuda, H. Takaya, K. Toriumi, T. Ito, T. Souchi, R. Noyori, *J. Am. Chem. Soc.* **1980**, *102*, 7932 – 7934; b) A. Miyashita, H. Takaya, T. Souchi, R. Noyori, *Tetrahedron,* **1984**, *40*, 1245 – 1253; c) H. Takaya, K. Mashima, K. Koyano, M. Yagi, H. Kumobayashi, T. Taketomi, S. Akutagawa, R. Noyori, *J. Org. Chem.* **1986**, *51*, 629 – 635; d) R. Noyori, H. Takaya, *Acc. Chem. Res.* **1990**, *23*, 345 – 350; e) R. Noyori, *Science* **1990**, *248*, 1194 – 1199; f) R. Noyori, T. Ohkuma, *Angew. Chem.* **2001**, *113*, 40 – 75; *Angew. Chem. Int. Ed.* **2001**, *40*, 40 – 73.

[5] a) M. J. Burk, *J. Am. Chem. Soc.* **1991**, *113*, 8518 – 8519; b) M. J. Burk, J. E. Feaster, W. A. Nugent, R. L. Harlow, *J. Am. Chem. Soc.* **1993**, *115*, 10125 – 10138; c) M. J. Burk, S. Feng, M. F. Gross, W. Tumas, *J. Am. Chem. Soc.* **1995**, *117*, 8277 – 8278; d) M. J. Burk, Y. M. Wang, J. R. Lee, *J. Am. Chem. Soc.* **1996**, *118*, 5142 – 5243; e) M. J. Burk, F. Bienewald, S. Challenger, A. Derrick, J. A. Ramsden, *J. Org. Chem.* **1999**, *64*, 3290 – 3298.

[6] Q. Jiang, Y. Jiang, D. Xiao, P. Cao, X. Zhang, *Angew. Chem.* **1998**, *110*, 1203 – 1207; *Angew. Chem. Int. Ed.* **1998**, *37*, 1100 – 1103.

[7] D. Xiao, Z. Zhang, X. Zhang, *Org. Lett.* **1999**, *1*, 1679 – 1681.

[8] a) A. Marinetti, V. Kruger, F.-X. Buzin, *Tetrahedron Lett.* **1997**, *38*, 2947 – 2950; b) A. Marinetti, J.-P. Genêt, S. Jus, D. Blanc, V. Ratovelomanana-Vidal, *Chem. Eur. J.* **1999**, *5*, 1160 – 1165.

[9] J. Holz, M. Quirmbach, U. Schmidt, D. Heller, R. Stürmer, A. Börner, *J. Org. Chem.* **1998**, *63*, 8031 – 8034.

[10] J. Holz, D. Heller, R. Stürmer, A. Börner, *Tetrahedron Lett.* **1999**, *40*, 7059 – 7062.

[11] T. Saito, T. Yokozawa, T. Ishizaki, T. Moroi, N. Sayo, T. Miura, H. Kumobayashi, *Adv. Synth. Catal.* **2001**, *343*, 264 – 267.

[12] E. P. Kyba, S. -T. Liu, R. L. Harris, *Organometallics* **1983**, *2*, 1877 – 1879.

[13] a) F. Hintze, D. Hoppe, *Synthesis* **1992**, 1216 – 1218; b) K. Tomooka, N. Komine, T. Sasaki, H. Shimizu, T. Nakai, *Tetrahedron Lett.* **1998**, *39*, 9715 – 9718.

[14] a) K. W. Kottsieper, U. Kühner, O. Stelzer, *Tetrahedron: Asymmetry* **2001**, *12*, 1159 – 1169; b) K. Matsumura, H. Shimizu, T. Saito, H. Kumobayashi, *Adv. Synth. Catal.* **2003**, *345*, 180 – 184.