DOI: 10.1002/adsc.200505241

Highly Air- and Water-Stable Fluorinated Ferrocenylphosphine-Aminophosphine Ligands and their Applications in Asymmetric Hydrogenations

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Received: June 8, 2005; Accepted: September 19, 2005

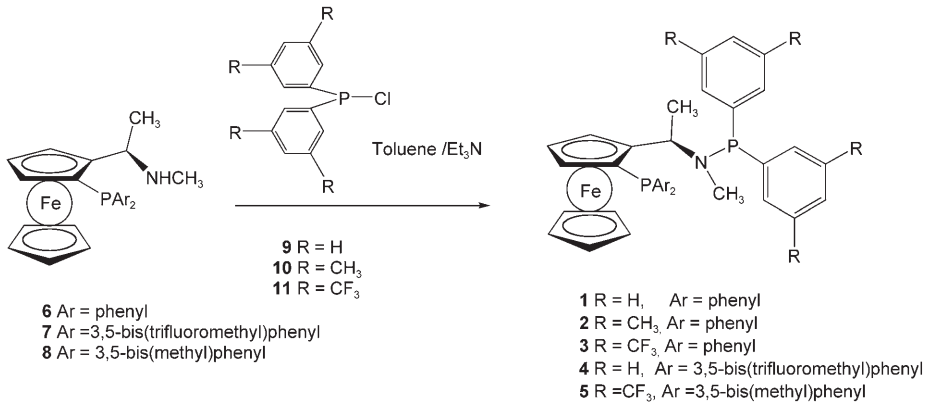
Abstract: Air- and water-stable fluorinated ferrocenylphosphine-aminophosphine ligands have been synthesized and applied to the Rh-catalyzed asymmetric hydrogenation of enamides and α-dehydroamino acid derivatives. These reactions afforded the corresponding products in good to excellent ees (up to 99.7% ee) and nearly quantitative yields. The combination of the remarkable air- and water-stability with excellent catalytic performance makes these catalysts excellent choices for practical applications.

Keywords: air-stable ligands; asymmetric hydrogenation; enamides; ferrocenylphosphine-aminophosphine ligands; rhodium

Asymmetric catalytic reactions have attracted much attention in recent years because of their great potential in making higher-value-added products.[1] In this respect, the use of chiral ligands has played a very important role.[2] So far many chiral ligands have been prepared and used for Rh- and Ru-catalyzed asymmetric hydrogenation.[3] Although moderate to excellent enantioselectivities have been achieved using these ligands, most of the catalytic reactions needed to be performed with the strict exclusion of oxygen and moisture, thus making them quite inconvenient for general organic synthesis and industrial applications. From a practical standpoint, it is desirable to develop effective, easily prepared chiral ligands and catalysts with high air- and water-stability, so that the associated catalytic reactions can be easily carried out in ordinary laboratory or industrial settings.

Chiral ligands with a ferrocenyl backbone have found useful applications in transition metal-catalyzed asymmetric hydrogenations.[1,3,4] Some well known examples include Hayashi's (aminoalkyl)ferrocenylphosphine ligands,[5] Togni's Josiphos-type ligands,[6] Burk's FerroTANE-type ligands,[7] Knochel's ferrocenyl ligands with two phosphanyl substituents,[8] Zhang's f-binaphane [9] and Spindler's Walphos-type ligands.[10] Recently, Baoz et al. reported the preparation of phosphinoferrocenylaminophosphines and their application in the rhodium-catalyzed asymmetric hydrogenation with high activities and enantioselectivities.[11] In our quest for highly efficient ligands in asymmetric hydrogenation,[12] we became interested in ferrocene-based ligands with high efficiency and stability. Herein we report the interesting findings of some new fluorinated phosphinoferrocenylaminophosphines in rhodium-catalyzed asymmetric hydrogenation. The distinctly high air- and water-stabilities of the fluorinated ligands as well as their Rh(I) complexes, combined with the high enantioselectivities in asymmetric hydrogenation, make them good choices for practical applications.

We first examined ligand **1** (Scheme 1) in hydrogenation of arylenamides, and relatively poor ee values were observed in contrast to the results obtained from the hydrogenation of α-dehydroamino acid derivatives under similar conditions (>99% ee).[11] This is not surprising because chiral ligands for asymmetric catalysis usually perform well for specific types of substrates. It is well-known that effectiveness of ligands might be changed substantially when their structures are modified.[3,13] In this pursuit we have prepared a series of new ligands with electron-donating or electron-withdrawing groups on the phenyl rings of the phosphine or amino-phosphine. The synthetic route for the target ligands is illustrated in Scheme 1. The reaction of diarylphosphorous



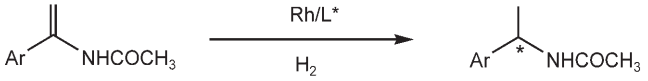
Scheme 1.

chlorides **9**–**11** with ferrocene-amines **6**–**8** in the presence of triethylamine gave the desired products **1**–**5** in 80–95% yield. We were delighted to find that ligand **3** was air-stable in solution. A chloroform solution of ligand **3** exposed to air and in the presence of water showed no change in the ^{31}P NMR spectrum even after two months. In contrast, ligands **1, 2** and **4** decomposed within 8 h, as expected. Other ligands, such as aminophosphine, phosphinite, and monodentate phosphoramidite, decomposed quickly under similar conditions. For example, bisaminophosphine ligand BDPAB[14]and phosphinite ligand BINAPO[15] decomposed completely in one hour; the monodentate phosphoramidite ligands Monophos[16] and H_8-Monophos[12b] decomposed within 24 h.

The new ligands (**2**–**5**) and ligand **1** were tested in the rhodium-catalyzed hydrogenation of arylenamide substrates **12a** and **b**. The three new ligands **2, 3** and **5** were found to be superior to ligand **1** (Table 1, entries 3–5 *vs.* entries 1 and 2). These results demonstrated the importance of the steric and electronic effects of the ligand on the enantioselectivities. Ligand **4**, which contained a 3,5-bis(trifluoromethyl)phenylphosphino group on the ferrocenyl ring, displayed a negative effect (entry 6). A preliminary screening of the solvent effect showed that there were no significant differences among dichloromethane, 2-propanol, toluene and THF (Table 1, entries 5, 7–10). THF was chosen as the solvent of choice for the rest of the study because it was slightly better than the other common organic solvents tested. Based on this interesting lead, we further studied ligands **3** and **5** in more detail.

An inconvenience of using rhodium phosphine complexes in catalytic hydrogenation is that most active rhodium-phosphine catalysts are air-sensitive. Since only a very tiny amount of catalyst is used in a laboratory study of hydrogenation reactions, the presence of even a small amount of air in the system can ruin the experiments. For this reason special equipment and tedious pretreatments are usually needed to get consistent results. Developing a highly effective chiral catalyst that is air-stable is thus highly desirable. In this regard we were delighted to find that not only ligand **3**, but also its rhodium complex were air-stable, even in solution. Surprisingly, catalytic hydrogenation reactions in the presence of air using the Rh-**3** complex prepared *in situ* in air showed essentially the same ee values for the chiral products as compared with those from the air-tight system (Table 2, entries 1–3 *vs.* Table 1, entry 9). The Rh-**3** complex prepared and kept in air for 8 h and then used for the hydrogenation of enamide **12a** showed no change in enantioselectivity (95.2% ee, entry 4). The stability of the cata-

Table 1. Asymmetric hydrogenation of aryl enamides **12a** and **12b** with different Rh-phosphinoferrocenylaminophosphines catalysts.[a]

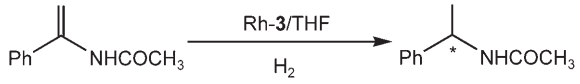


Entry	Ligand	Substrate	Ar	Solvents	t [h]	Ee [%][b]
1	**1**	**12a**	Ph	CH_2Cl_2	10	70.0
2	**1**	**12b**	*p*-F_3C-C_6H_4	CH_2Cl_2	10	73.1
3	**2**	**12a**	Ph	CH_2Cl_2	8	80.6
4	**2**	**12b**	*p*-F_3C-C_6H_4	CH_2Cl_2	8	79.6
5	**3**	**12a**	Ph	CH_2Cl_2	16	94.6
6	**4**	**12a**	Ph	CH_2Cl_2	10	35.0
7	**5**	**12a**	Ph	*i*-PrOH	16	94.4
8	**3**	**12a**	Ph	Toluene	16	93.5
9	**3**	**12a**	Ph	THF	16	96.5
10	**5**	**12a**	Ph	THF	8	96.2

[a] Reaction conditions: all the catalysts used in the reactions were prepared *in situ*. Hydrogen pressure was 300 psi in all reactions; substrate:catalyst = 100:1. All the reactions were carried out at ambient temperature; quantitative yields were obtained in all cases.

[b] The ees were determined by chiral GC analysis using a 50 m × 0.25 mm Chrompack chiral fused silica chirasil-L-VAL column. The *S* configuration was assigned by comparing the experimental results with published data.

Table 2. The investigation of the stability of Rh-**3** in water and air.[a]



Entry	S/C	Catalyst solution exposed to air [h]	H_2O	ee [%][b]
1	100	–	–	96.1
2	500	–	–	95.8
3	100	0.5	–	95.5
4	100	8	–	95.2
5	100	0.5	5%	95.1
6	100	0.5	30%	77.2

[a] The catalyst used in all the reactions was prepared *in situ* in air; all the reactions were performed at room temperature and the hydrogen pressure was 300 psi.
[b] The ee values were determined using the method described in Table 1.

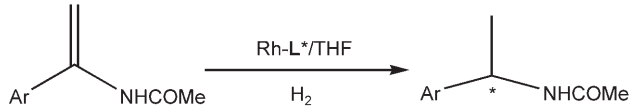
lyst to water was also examined by adding 5% of water to the reaction system containing the Rh-**3** complex and the enamide **12a**. The enantioselectivity remained unchanged with quantitative yield of the product (entry 5). This property is desirable in industrial applications as no laborious drying of solvents is needed when the catalysts have enough moisture stability. When water content of the solvent was increased to 30%, the conversion was still nearly quantitative, indicative of the high activity of the catalyst even in the presence of a high concentration of water. However, the ee value decreased to 77.2% (entry 6), which confirmed that water was not a suitable solvent for this enantioselective hydrogenation reaction.

The enantioselectivity of the Rh-**3** complex was also examined with a variety of arylenamides under the optimized conditions at room temperature, and the results are summarized in Table 3. All the substrates were quantitatively converted to the desired chiral products with ee values ranging from 92.1% to 99.7%. Changing the reaction temperature to 5 °C increased the enantioselectivity noticeably, and some of the desired products were almost optically pure (entries 9–15).

The enantioselectivities of ligands **2**–**5** were also examined in the Rh-catalyzed hydrogenation of α-dehydroamino acid derivatives (Table 4). Complete conversions and more than 90% enantioselectivities have been achieved with ligands **2**–**5** at ambient temperature. Among the ligands employed, both **2** and **3** gave the best results (entries 1–4). The use of ligands **4** and **5** led to lower ees (entries 5 and 6). These results are comparable to those achieved by using ligand **1**.[10]

In summary, we have developed phosphinoferrocenylaminophosphines ligands **2, 3, 4** and **5** and applied them to asymmetric hydrogenations. Good to excellent results were obtained. The study revealed that Rh-**3** and

Table 3. Asymmetric hydrogenation of various arylenamides catalyzed by Rh-**3**.[a]

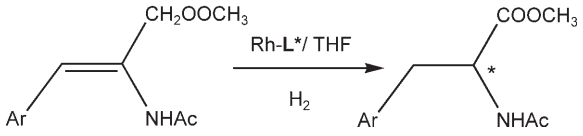


12a – h

Entry	Substrate	Ar	S/C	T [°C]	t [h]	ee [%][b]
1	**12a**	Ph	100	rt	16	96.5
2	**12a**	Ph	200	rt	16	95.8
3	**12a**	Ph	500	rt	16	96.4
4	**12a**	Ph	1000	rt	16	95.8
5	**12b**	*p*-F_3C-C_6H_4	500	rt	16	97.1
6	**12c**	*p*-Br-C_6H_4	500	rt	16	99.3
7	**12d**	*p*-CH_3-C_6H_4	500	rt	16	92.1
8	**12f**	*p*-CH_3O-C_6H_4	500	rt	16	93.5
9	**12a**	Ph	500	5	30	98.3
10	**12b**	*p*-F_3C-C_6H_4	500	5	30	98.6
11	**12c**	*p*-Br-C_6H_4	500	5	30	99.7
12	**12d**	*p*-CH_3-C_6H_4	500	5	30	99.4
13	**12f**	*p*-CH_3O-C_6H_4	500	5	30	99.3
14	**12g**	*m*-CH_3-C_6H_4	500	5	30	98.5
15	**12h**	*m*-CH_3O-C_6H_4	500	5	30	99.0

[a] The preparation of catalyst and the reaction conditions were the same as those in Table 2.
[b] The ee values were determined using the same method as described in Table1.

Table 4. Applications of ligands **2**–**5** in **the** Rh-catalyzed asymmetric hydrogenation of α-dehydroamino acid derivatives.[a]



13a Ar = Ph
13b Ar = *p*- NO_2-C_6H_4

Entry	Ligand	Substrate	ee [%][b]
1	**2**	**13a**	99.0
2	**2**	**13b**	99.5
3	**3**	**13a**	99.2
4	**3**	**13b**	99.7
5	**4**	**13a**	96.1
6	**5**	**13a**	98.5

[a] The catalyst used in all the reactions was prepared *in situ*. Hydrogen pressure was 300 psi in all reactions; substrate:catalyst = 200:1 (molar ratio); All the reactions were carried out at ambient temperature.
[b] The ees were determined by chiral GC analysis using a Chrompack chiral fused silica 25 m × 0.25 mm chirasil-L-VAL column. The *S* configuration was assigned based on comparison with published data.

Rh-**5** complexes displayed remarkable enantioselectivity (up to 99.7% ee). Their air- and water-stabilities, combined with their excellent enantioselectivities, make these catalysts good choices for practical applications.

Experimental Section

General Methods

All solvents were used as received except where indicated. All reagents were used as received from Aldrich Chemical Company except where indicated. (R)-*N,N*-Dimethyl-1-[(S)-2-(diphenylphosphino)ferrocenyl]ethylamine, (*R*)-*N,N*-dimethyl-1-[(S)-2-(di-3,5-trifluoromethylphenylphosphino)ferrocenyl]-ethylamine and (*R*)-*N,N*-dimethyl-1-[(S)-2-[(di-3,5-dimethylphenylphosphino)ferrocenyl]ethylamine were prepared according to methods reported in the literature.[17] Compounds **6**, **7** and **8** were prepared according to a literature procedure.[11]

(*R*)-*N*-Methyl-*N*-[di-3,5-dimethylphenyl]phosphino-1-[(*S*)-2-(diphenylphosphino)ferrocenyl]ethylamine (2)

Amine **6** (427 mg, 1.0 mmol) was dissolved in 10 mL of toluene under a nitrogen atmosphere. Triethylamine (0.29 mL, 2.1 mmol) and DMAP (20 mg) were added. The solution was cooled in ice/water and chlorodi[3,5-dimethylphenyl]phosphine (1.0 mmol in toluene) was added dropwise. The reaction mixture was allowed to warm to ambient temperature and stirred overnight and the resulting reactions mixture was filtered through a flash silica gel column and washed with toluene. The combined filtrate was concentrated under vacuum to afford **2** as a yellow foam; yield: 613 mg (92%). ^{1}H NMR (500 MHz, $CDCl_3$): δ = 7.68–7.65 (m, 2H), 7.39–7.37 (m, 3H), 7.26–7.16 (m. 2H), 7.05–6.89 (m, 6H), 6.77–6.76 (d, 3H), 4.80–4.68 (m, 1H), 4.60 (s, 1H), 4.39 (s, 1H), 4.11 (s, 1H), 3.76 (s, 5H), 2.27 (d, 3H, *J* = 3.5 Hz), 2.19 (s, 6H), 2.04 (s, 6H), 1.59 (d, 3H, *J* = 7 Hz); ^{13}C NMR (125 MHz, $CDCl_3$): δ = 142.23, 142.16, 140.23, 140.15, 139.74, 139.59, 139.49, 139.41, 137.80, 136.94, 136.89, 136.87, 136.81, 135.87, 135.68, 131.83, 131.71, 131.12, 130.95, 129.90, 129.73, 129.58, 129.48, 129.14, 129.00, 128.20, 128.96, 127.90, 127.47, 127.43, 126.70, 125.27, 98.84, 98.75, 98.60, 98.52, 75.91, 75.80, 71.74, 71.71, 69.91, 69.60, 69.58, 69.44, 57.86, 57.58, 33.04, 32.96, 21.43, 21.31, 21.21, 19.64, 19.57; ^{31}P NMR (200 MHz, $CDCl_3$): δ = 54.52, −22.53; HRMS (EI): *m/z* = 667.2225 [calcd. for $C_{41}H_{43}FeNP_2$ (M^+): 667.2220]; $[\alpha]_D^{20}$: −301° (*c* 0.88, toluene).

(*R*)-*N*-Methyl-*N*-[di-3,5-trifluoromethylphenyl]-phosphino-1-[(*S*)-2-(diphenylphosphino)ferrocenyl]-ethylamine (3)

A similar procedure as for the preparation of **2** was used, affording the product **3**; yield: 821 mg (93%). ^{1}H NMR (500 MHz, $CDCl_3$): δ = 7.76–7.37 (m, 11H), 6.89–6.77 (m, 5H), 4.90–4.88 (m, 1H), 4.68 (s, 1H), 4.51 (s, 1H), 4.19 (s, 1H), 3.82 (m, 5H), 2.24 (d, 3H, *J* = 2.0 Hz), 1.80–1.78 (d, 3H, *J* = 7.0 Hz); ^{13}C NMR (125 MHz, $CDCl_3$): δ = 142.20, 142.02, 141.62, 141.45, 140.43, 140.38, 138.89, 138.83, 135.70, 135.52, 132.28, 132.10, 131.91, 131.73, 131.64, 131.58, 131.54, 131.51, 131.32, 131.27, 131.23, 131.01, 129.44, 128.18, 128.11, 127.49, 127.45, 127.13, 124.28, 124.26, 122.76, 122.44, 122.11, 122.08, 97.61, 97.55, 97.38, 97.31, 75.37, 75.27, 72.27, 72.24, 70.20, 69.94, 69.92, 69.31, 33.72, 33.63, 20.99, 20.93; ^{31}P NMR (200 MHz, $CDCl_3$): δ = 50.26 (d, *J* = 9.80 Hz), −24.63 (d, *J* = 9.80 Hz); HRMS (EI): *m/z* = 883.1094 [calcd for $C_{41}H_{31}F_{12}FeNP_2$ (M^+): 883.1089]; $[\alpha]_D^{20}$: −253° (*c* 0.8, toluene).

(*R*)-*N*-Methyl-*N*-diphenylphosphino-1-[(*S*)-2-(di-3,5-trifluoromethylphenylphosphino) ferrocenyl]ethyl-amine (4)

A similar procedure as for the preparation of **2** was used, affording the product **4**; yield: 780 mg (89%). ^{1}H NMR (500 MHz, $CDCl_3$): δ = 8.08 (d, *J* = 7.5 Hz, 2H), 7.99 (s, 1H), 7.67 (s, 1H), 7.36 (m, 2H), 7.29 (m, 4H), 7.18 (m,1H), 7.00 (m, 1H), 6.82 (m, 4H), 5.04 (q, *J* = 6.5 Hz, 1H), 4.630 (s, 1H), 4.54 (s, 1H), 3.92 (s, 1H), 3.80 (s, 5H), 2.24 (d, *J* = 2.5 Hz, 3H), 1.53 (d, *J* = 6.5 Hz, 3H); ^{13}C NMR (125 MHz, $CDCl_3$): δ = 144.54, 144.42, 142.04, 141.91, 140.09, 139.92, 138.65, 137.90, 135.31, 135.14, 132.98, 132.81, 132.06, 131.90, 131.37, 131.29, 131.00, 129.64, 129.07, 128.44, 128.25, 128.00, 127.90, 127.85, 127.44, 127.40, 126.36, 125.33, 124.19, 123.57, 122.02, 121.74, 119.84, 98.42, 98.06, 72.26, 72.17, 71.39, 71.11, 70.53, 69.88, 58.71, 29.31, 29.22, 17.42; ^{31}P NMR (200 MHz, $CDCl_3$): δ = 62.435, −19.756; HRMS (EI): *m/z* = 883.1082 [calcd. for $C_{41}H_{31}F_{12}FeNP_2$ (M^+): 883.1089]; $[\alpha]_D^{20}$: -208^0 (*c* 0.48, toluene).

(*R*)-*N*-Methyl-*N*-[di-3,5-trifluorodimethylphenyl]-phosphino-1-[(*S*)-2-[(di-3,5-dimethylphenylphosphino)-ferrocenyl]ethylamine (5)

A similar procedure as for the preparation of **2** was used, affording the product **5**; yield: 873 mg (93%). ^{1}H NMR (500 MHz, $CDCl_3$): δ = 1.75 (d, *J* = 7.0 Hz, 3H), 1.94 (s, 6H), 2.36 (d, *J* = 5.0 Hz, 3H), 2.39 (s, 6H), 3.82 (s, 5H), 4.22 (s, 1H), 4.49 (s, 1H), 4.62 (s, 1H), 4.92–4.96 (m, 1H), 6.45 (d, *J* = 7.0 Hz, 2H), 6.53 (s, 1H), 7.07 (s, 1H), 7.32 (m, 2H), 7.48 (m, 2H), 7.69–7.76 (m, 4H); ^{13}C NMR (125 MHz, $CDCl_3$): δ = 142.77, 142.62, 142,09,141.88, 140.49, 140.43, 139.18, 139.12, 137.60, 137.53, 136.76, 136.72, 133.68, 133.49, 133.28, 133.09, 131.39, 131.26, 131.13, 129.60, 129.47, 128.97, 124.47, 124,43, 123.07, 122.26, 122.08, 96.96, 96.88, 96.73, 96.66, 77.13, 72.86, 72.82, 70.11, 70.05, 69.53, 58.98, 58.90, 58.68, 58.61, 21.56, 21.10, 20.40, 20.35; ^{31}P NMR (200 MHz, $CDCl_3$): δ = 51.648, −23.747; HRMS (EI): *m/z* = 939.1707 [calcd. for $C_{45}H_{39}F_{12}FeNP_2$ (M^+): 939.1715]; $[\alpha]_D^{20}$: −219° (*c* 0.56, toluene).

Typical Procedure for Asymmetric Hydrogenation

The catalyst was made in *situ* by mixing $[Rh(COD)_2]BF_4$ (2.0 mg, 0.005 mmol) and ligand **3** (4.9 mg, 0.0055 mmol) in THF (1 mL) for 10 min. A small portion of the catalyst solution (0.1 mL) was transferred into a 50-mL glass-lined stainless steel autoclave, which contained the substrate (0.1 mmol) and a magnetic stirring bar. The reactor was charged with hydrogen gas, and the solution was stirred at the required temperature for a predetermined period of time. After the reaction

was completed, the hydrogen gas was released. The ee value of the product was determined by GC analysis with a chiral GC column as indicated in the footnotes of the Tables.

Acknowledgements

We thank the University Grants Committee of Hong Kong (Areas of Excellence Scheme, AOE P/10–01) and the Hong Kong Polytechnic University ASD Fund for the financial support of this study.

References and Notes

[1] a) R. Noyori, *Asymmetric Catalysis in Organic Synthesis*, Wiley, New York, **1994**; b) E. N. Jacobsen, A. Pfaltz, H. Yamamoto (Eds.), *Comprehensive Asymmetric Catalysis*, Springer, Berlin, **1999**, Vol. 1; c) I. Ojima, *Catalytic Asymmetric Synthesis*, Wiley-VCH, New York, **2000**; d) G. Lin, Y. Li, A. S. C. Chan, *Principles and Applications of Asymmetric Synthesis*, Wiley, New York, **2001**.

[2] a) H.-P. Jacqueline, *Chiral Auxiliaries and Ligands in Asymmetric Synthesis*, Wiley, New York, **1995**; b) J. Jacques, A. Collet, S. H. Wilen, *Enantiomers, Racemates, and Resolutions*, Wiley, New York, **1981**.

[3] a) H. U. Blaser, C. Malan, B. Pugin, F. Spindler, H. Steiner, M. Studer, *Adv. Synth. Catal.* **2003**, *345*, 103; b) W. Tang, X. Zhang, *Chem. Rev.* **2003**, *103*, 3029.

[4] a) A. Togni, T. Hayashi, *Ferrocenes – Homogeneous Catalysis, Organic Synthesis, Material Science*, VCH, Weinheim, **1995**; b) A. Togni, R. L. Halterman, *Metallocenes*, Vol. 2, Wiley-VCH, Weinheim, **1998**; c) C. J. Richards, A. J. Locke, *Tetrahedron: Asymmetry* **1998**, *9*, 2377.

[5] T. Hayashi, N. Kawamura, Y. Ito *J. Am. Chem. Soc.*, **1987**, *109*, 7876.

[6] A. Togni, C. Breutel, A. Schnyder, F. Spindler, H. Landert, A. Tijani, *J. Am. Chem. Soc.* **1994**, *116*, 4062.

[7] U. Berens, M. J. Burk, A. Gerlach, W. Hems, *Angew. Chem. Int. Ed.* **2000**, *39*, 1981.

[8] a) T. Ireland, G. Grossheimann, C. Wieser-Jeunesse, P. Knochel, *Angew. Chem. Int. Ed.* **1999**, *38*, 3112; b) M. Lotz, G. Kramer, P. Knochel, *Chem. Commun*. **2002**, 2546.

[9] D. Xiao, X. Zhang, *Angew. Chem. Int. Ed.* **2001**, *40*, 3425.

[10] T. Stum, W. Weissensteiner, F. Spindler, *Adv. Synth. Catal.* **2003**, *345*, 160.

[11] a) N. W. Boaz, S. D. Debenham, E. B. Mackenzie, S. E. Large, *Org. Lett.* **2002**, *4*, 2421; b) N. W. Boaz, S. D. Debenham, S. E. Large, M. K. Moore, *Tetrahedron: Asymmetry* **2003**, *14*, 3575; c) N. W. Boaz, E. B. Mackenzie, S. D. Debenham, S. E. Large, J. A. Ponasik, *J. Org. Chem.* **2005**, *70*, 1872.

[12] a) L. Xu, K. Lam, J. Ji, J. Wu, Q. Fan, W. Lo, A. S. C. Chan, *Chem. Commun*. **2005**, 1390; b) X. Jia, R. Guo, X. Li, X. Yao, A. S. C. Chan, *Tetrahedron Lett*. **2002**, *43*, 5541; c) X. Jia, X. Li, L. Xu, Q. Shi, X. Yao, A. S. C. Chan, *J. Org. Chem.* **2003**, *68*, 4539; d) X. Li, X. Jia, G. Lu, T. L. Au-Yeung, K. Lam, T. W. Lo, A. S. C. Chan, *Tetrahedron: Asymmetry* **2003**, *14*, 2687.

[13] For some recent examples, see: a) J. Hayashi, S. Hirate, K. Kitayama, H. Tsiji, A. Torii, Y. Uoaumi, *J. Org. Chem.* **2001**, *66*, 1441; b) J. Wu, X. Chen, R. Guo, C. Yeung, A. S. C. Chan, *J. Org. Chem.* **2003**, *68*, 2490; c) J. Wu, H. Chen, W. Kwok, R. Guo, Z. Zhou, C. Yeung, A. S. C. Chan, *J. Org. Chem.* **2002**, *67*, 7908; d) A. L. Casalnuovo, T. V. RajanBabu, T. A. Ayers, T. H. Warren, *J. Am. Chem. Soc.* **1994**, *116*, 9869.

[14] F. Zhang, C. Pai, A. S. C. Chan, *J. Am. Chem. Soc*. **1998**, *120*, 5808.

[15] R. H. Grubbs, R. A. DeVries, *Tetrahedron Lett*. **1977**, 1879.

[16] M. Berg, A. J. Minnaard, Z. P. Schudde, J. Esch, A. H. M. Vries, J. G. Vries, B. L. Feringa, *J. Am. Chem. Soc*. **2000**, *122*, 11539.

[17] T. Hayashi, T. Mise, M. Fukushima, M. Kagotani, N. Nagashima, Y. Hamada, A. Matsumoto, S. Kawakami, M. Konishi, K. Yamamoto, M. Kumada, *Bull. Chem. Soc. Jpn*. **1980**, *53*, 1138.

