# A Novel Easily Accessible Chiral Ferrocenyldiphosphine for Highly Enantioselective Hydrogenation, Allylic Alkylation, and Hydroboration Reactions

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**Abstract:** The new ligand (*R*)-1-[(*S*)-2-(diphenylphosphino)ferrocenyl]ethyldicyclohexylphosphine ((*R*)-(*S*)-**3a**) was prepared in two steps from the commercially available *N*,*N*-dimethyl-(*R*)-1-ferrocenylethylamine via *N*,*N*-dimethyl-(*R*)-1-[(*S*)-2-(diphenylphosphino)ferrocenyl]ethylamine ((*R*)-(*S*)-**1**) in good yields. The crucial second step, i.e., the substitution of the dimethylamino group by the dicyclohexylphosphino fragment, was achieved in 88% yield under complete retention of configuration in acetic acid solvent, using dicyclohexylphosphine as a reagent. This methodology constitutes an easy access to a class of chiral chelating diphosphines, where the two ligating moieties can be varied independently from one another, thus allowing the study of both the steric and electronic influence of the ligands on stereoselectivity. Compound **3a** was used in Rh-catalyzed asymmetric hydrogenation and hydroboration as well as in Pd-catalyzed allylic alkylation reactions giving high enantioselectivities (up to 99%).

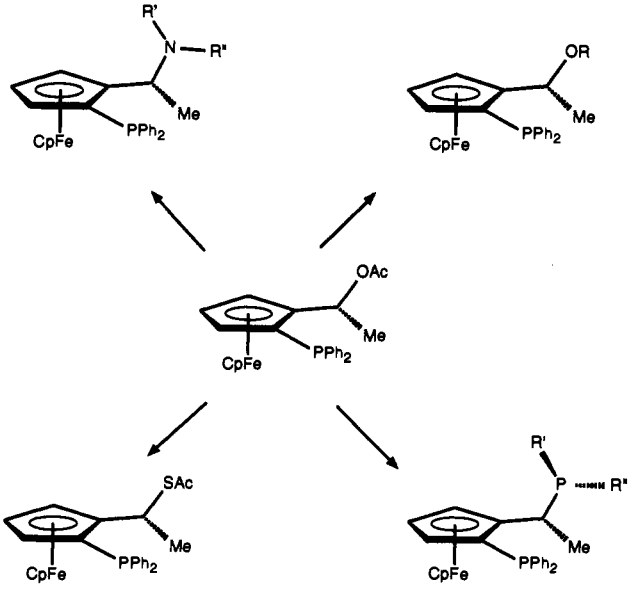
## Introduction

It is not common that a chiral ligand for asymmetric catalysis equally performs in a variety of reactions. The general observation is that a certain chiral ligand can be successfully employed only for a specific combination of reaction type, catalyst, and substrate. An important exception is the *$C_2$-symmetric*[1] ligand BINAP.[2] The wide scope of this ligand has been demonstrated particularly well for the enantioselective hydrogenation reactions of olefins and ketones as well as for the isomerization of enamines.[3]

Chiral chelating phosphines derived from ferrocene constitute a unique class of *asymmetric* ligands.[4] Many of the so far known compounds of this type impart high enantioselectivities to several transition-metal-catalyzed reactions, mainly because they possess the crucial feature, distinguishing them from other chiral chelating diphosphines, of having a functionalized side chain which can be modeled to fulfill the specific purpose of interacting with the substrate.[5] However, because of synthetic reasons, as it is the case for most chiral diphosphines known, these ligands contain *two identical phosphino groups* (for the vast majority of the cases a diphenylphosphino group) attached to the ferrocene moiety in 1,1′-position.[6] The introduction of the desired side chain is completed via retentive nucleophilic displacement of a suited leaving group at the pseudo-benzylic position,[7] as illustrated in Scheme 1. This $S_N1$-type reaction, characteristic of this system, is typically accomplished using an excess of a secondary amine or an alcohol as nucleophile, usually in refluxing methanol.[6] We recently extended this methodology to the sulfur nucleophile KSAc and have shown that anhydrous acetic acid is the solvent of choice for this transformation.[8]

We report herein a facile synthesis of new *asymmetric* chelating ferrocenyldiphosphines, which were found to form very active and highly enantioselective catalysts for different reactions. Furthermore, the synthetic approach to these new ligands provides considerable scope for varying the substituents at the phosphorus atoms, the only limiting factor being the availability of the desired secondary phosphine reagents (*vide infra*).

**Scheme 1**

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(1) For a discussion of the role and importance of $C_2$-symmetric ligands, see: Whitesell, J. K. *Chem. Rev.* **1989**, *89*, 1581–1590.

(2) See, e.g.: Noyori, R.; Takaya, H. *Acc. Chem. Res.* **1990**, *23*, 345–350, and references cited therein.

(3) For recent reviews, see: (a) Takaya, H.; Ohta, T.; Noyori, R. In *Catalytic Asymmetric Synthesis*; Ojima, I., Ed.; VCH Publishers: New York, 1993; pp. 1–39, and references cited therein. (b) Akutagawa, S.; Tani, K. *Catalytic Asymmetric Synthesis;* pp 41–61.

(4) For reviews, see: (a) Hayashi, T. In *Organic Synthesis: An Interdisciplinary Challenge*; Streith, J., Prinzbach, H., Schill, G., Eds.; Blackwell: 1985; pp 35–42. (b) Hayashi, T. *Pure Appl. Chem.* **1988**, *60*, 7–12. (c) Hayashi, T.; Kumada, M. *Acc. Chem. Res.* **1982**, *15*, 395–401. (d) Hayashi, T.; Kumada, M. In *Asymmetric Synthesis*; Morrison, J. D., Ed.; Academic Press: Orlando, FL, 1985; Vol. 5, pp 147–169.

(5) Sawamura, M.; Ito, Y. *Chem. Rev.* 1992, *92*, 857–871.

(6) Hayashi, T.; Mise, T.; Fukushima, M.; Kagotani, M.; Nagashima, M.; Hamada, Y.; Matsumoto, A.; Kawakami, S.; Konishi, M.; Yamamoto, K.; Kumada, M. *Bull. Chem. Soc. Jpn.* **1980**, *53*, 1138–1151.

(7) Gokel, G. W.; Marquarding, D.; Ugi, I. K. *J. Org. Chem.* **1972**, *37*, 3052–3058.

(8) (a) Togni, A.; Rihs, G.; Blumer, R. E. *Organometallics* **1992**, *11*, 613–621. (b) Togni, A.; Häusel, R. *Synlett* **1990**, 633–635.

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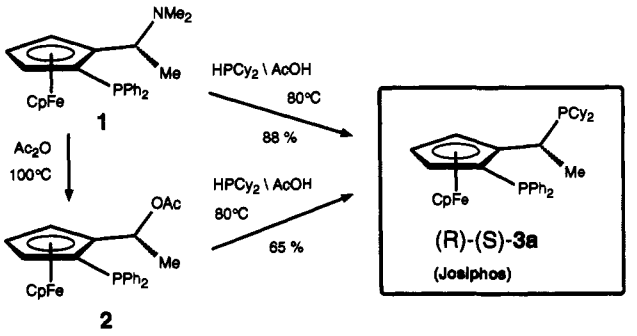
**Scheme 2**




## Results and Discussion

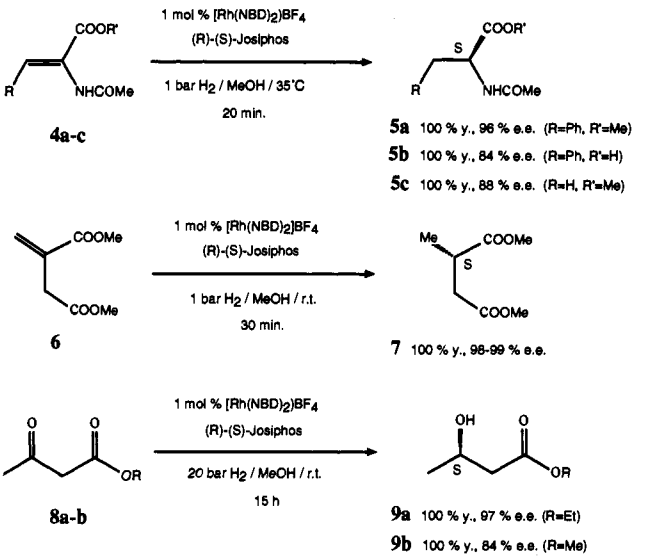
We will concentrate our discussion on the specific new ligand (*R*)-1-[(*S*)-2-(diphenylphosphino)ferrocenyl]ethyldicyclohexylphosphine, (*R*)-(*S*)-**3a**.[9] This compound is accessible directly from the amine (*R*)-(*S*)-**1**[10] and using only a slight excess of dicyclohexylphosphine as the nucleophile, in acetic acid solvent at 80 °C. It is isolated in high yield (88%) by crystallization from ethanol with no need of chromatographic purification, and the synthesis can be accomplished on a large scale (≤100 g). Compound (*R*)-(*S*)-**3a** is also formed, albeit in lower yields, by following the more classical procedure involving the intermediate acetate (*R*)-(*S*)-**2** (see Scheme 2).[6] The analogous ligands (*S*)-1-[(*R*)-2-(diphenylphosphino)ferrocenyl]ethyldiphenylphosphine,[11] (*S*)-(*R*)-**3b**, and (*R*)-1-[(*S*)-2-(diphenylphosphino)ferrocenyl]ethyldi-*tert*-butylphosphine, (*R*)-(*S*)-**3c**, have also been prepared with the aim of defining the steric and electronic influence of the phosphino group attached to the pseudobenzylic center of the ferrocenylethyl moiety. A comparison of the three ligands from the point of view of both selectivity and activity was carried out in the context of the Pd-catalyzed allylic alkylation (*vide infra*).

Ligand (*R*)-(*S*)-**3a** has been used in asymmetric rhodium-catalyzed hydrogenation and hydroboration as well as palladium-catalyzed allylic alkylation reactions. The results of the hydrogenation reactions are summarized in Scheme 3. Thus, reaction of methyl acetamidocinnamate, **4a**, under 1 bar of hydrogen pressure, in methanol at 35 °C, in the presence of 1 mol % of the catalyst (formed in situ from the reaction of **3a** with $[Rh(NBD)_2]BF_4$) afforded a quantitative yield of the hydrogenation product (*S*)-**5a** in 96% ee.[12] This result is comparable to those obtained with the best $C_2$-symmetric diphosphines reported in the literature.[13] On the other hand, when acetamidocinnamic acid (**4b**) was used as a substrate, in ethanol at 5 °C, a significantly lower enantioselectivity of 84% was obtained. The related 1,1-disubstituted olefin methyl acetamidoacrylate (**4c**) gave similar results (88% ee, in methanol at 40 °C with 0.5 mol % catalyst).

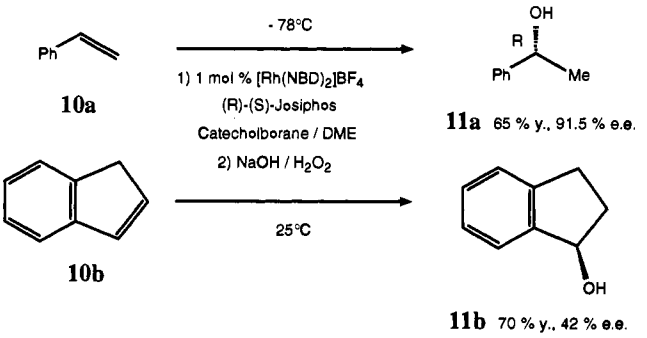
An unprecedented high enantioselectivity was obtained in the hydrogenation of dimethyl itaconate, **6**, under similar conditions. A quantitative yield of dimethyl (*S*)-2-methylsuccinate, **7**, in an optical purity of 98–99%,[12] was isolated after a reaction time of 0.5 h, by using 1 mol % of catalyst.[14] A catalyst to substrate ratio of 1:1000 afforded complete conversion of **6** in 3 h and an ee of 97.5%. Furthermore, the high pressure (20 bar $H_2$) hydrogenation of ethyl 3-oxobutyrate (**8a**) afforded the corresponding β-hydroxyester (methyl *S*-3-hydroxybutyrate, **9a**) in both high yield and enantioselectivity. An ee of 97% was determined by GC after conversion to the corresponding trifluoroacetoxy derivative with trifluoroacetic anhydride. Whereas enantioselectivities beyond 99% have been obtained for this type of substrates with the ruthenium/BINAP system,[2,3a] ee's as high as 97% do not appear to have been achieved with rhodium catalysts. Surprisingly, the hydrogenation of *methyl* 3-oxobutyrate gave a significantly lower selectivity (84% ee) under the same conditions. There is no obvious reason that can explain this relatively strong detrimental effect, going from the ethyl to the methyl ester.

A high enantioselectivity was also obtained in the rhodium-catalyzed hydroboration of styrene with catecholborane,[15] followed by oxidation with hydrogen peroxide, as shown in Scheme 4. Thus, the formation of 1-phenylethanol, **11a**, occurs with a high degree of enantioface discrimination, when carried out at −78 °C

**Scheme 3**




**Scheme 4**




(9) Because of the rather long systematic name of compound **3a**, we use, in our laboratories, to refer to this ligand as to **Josiphos**, from the name of the technician who first prepared it.

(10) (*R*)-(*S*)-**1** is prepared in one step from *N*,*N*-dimethyl-1-(*R*)-ferrocenylethylamine (see ref 6). Both enantiomers of this amine are commercially available.

(11) This ligand has been previously prepared by the reaction of the acetate compound **2** with an excess of diphenylphosphine in refluxing methanol (see ref 6).

(12) Optical purities were determined by capillary GC using chiral stationary phases (50 m CHIRASIL-L-Val, 50 m FS Lipodex E) and /or by HPLC (25 cm Daicel Chiralcel ODH), as described in the Experimental Section.

(13) See, e.g.: Koenig, K. E. In *Asymmetric Synthesis*; Morrison, J. D., Ed.; Academic Press: Orlando, FL, 1985; Vol. 5, pp 71–101. For more recent developments, see, e.g.: Burk, M. J. *J. Am. Chem. Soc.* **1991**, *113*, 8518–8519.

(14) An enantioselectivity of 99%, determined on the basis of optical rotation, was reported by Chiba et al. (Chiba, T.; Miyashita, A.; Nohira, H.; Takaya, H. *Tetrahedron Lett.* **1991**, *32*, 4745–4748). The axial-chiral ligand BICHEP was used.

(15) For a recent review, see: (a) Burgess, K.; Ohlmeyer, M. J. In *Homogeneous Transition Metal Catalyzed Reactions* (*Adv. Chem. Ser. 230*); Moser, W. R., Slocum, D. W., Eds.; American Chemical Society: Washington, DC, 1992; pp 163–177. For specific examples of asymmetric hydroboration reaction catalyzed by rhodium, see: (b) Hayashi, T.; Matsumoto, Y.; Ito, Y. *J. Am. Chem. Soc.* **1989**, *111*, 3426–3428. (c) Matsumoto, Y.; Hayashi, T. *Tetrahedron Lett.* **1991**, *32*, 3387–3390. (d) Hayashi, T.; Matsumoto, Y.; Ito, Y. *Tetrahedron: Asymmetry* **1991**, *2*, 601–612. (e) Burgess, K.; van der Donk, W. A.; Ohlmeyer, M. J. *Tetrahedron: Asymmetry* **1991**, *2*, 613–621.

in dimethoxyethane over a period of 10 h, using 2 mol % of catalyst ($[Rh(NBD)_2]BF_4$ and (*R*)-(*S*)-**3a** used as precursors). Only a very low amount (<1%) of the regioisomer 2-phenylethanol was formed. The product was isolated in 65% chemical yield and 91.5% optical purity.[12] This result again compares with the best selectivities so far reported in the literature for this particular reaction.[15d] However, an important drawback of this catalytic hydroboration is that styrene seems to be the only substrate which reacts at low temperature. In fact, when sterically more demanding olefins were used, the reaction had to be conducted at room temperature, in order to obtain complete conversion within a reasonable time. Thus indene (**10b**) was converted into *R*-1-indanol (**11b**) using 1 mol % of catalyst, but the enantioselectivity was only 42% (for comparison, the hydroboration of styrene at room temperature afforded **11a** in 60% ee). Under these conditions 5% of the achiral isomer 2-indanol also formed as a byproduct. On the other hand, the regioselectivity was complete in the case of norbornene (**10c**). The only product that could be detected after the oxidative workup was *R-exo*-norbornanol (**11c**), but the optical purity was very poor (7% based on optical rotation).[15d] Finally, when iridium was used instead of rhodium, even the reaction of styrene was much slower and less regioselective, although **11a** was obtained in 77% ee at room temperature. These results indicate that, for hydroboration, the increased basicity of the phosphine **3a**, with respect to all other chiral bis(diphenylphosphino) ligands reported in the literature,[15] constitutes a severe activity decreasing factor.

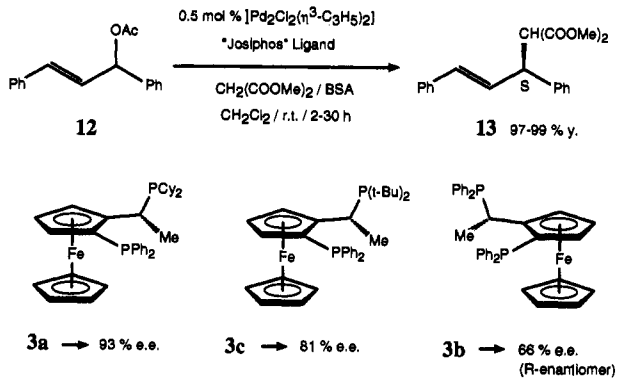
Ligand **3a** was also successfully applied in the palladium-catalyzed substitution reaction of allylic acetates by soft carbon nucleophiles.[16] Thus, reaction of racemic 1,3-diphenyl-3-acetoxypropene, **12**, with dimethyl malonate, under the conditions reported by Pfaltz and co-workers,[16d] and in the presence of 1 mol % of catalyst (generated in situ either from $[Pd_2(\eta^3\text{-}C_3H_5)_2Cl_2]$ and the ligand (*R*)-(*S*)-**3a**, or from the complex $[Pd(\eta^3\text{-}C_3H_5)((R)\text{-}(S)\text{-}3)]CF_3SO_3$) afforded the alkylation product (*S*)-**13** in nearly quantitative yield and with an enantioselectivity of 93% (reaction time 3 h, see Scheme 5).[12] This result shows that it is possible to achieve a very high stereoselection for this particular substrate, by using a ferrocenyl ligand which does not incorporate a functionality capable of a secondary interaction, as is the case for Hayashi's ferrocenylphosphines used in allylic alkylation.[17] Furthermore, when (*S*)-BINAP was used instead of (*R*)-(*S*)-**3a** under the same conditions, the product (*R*)-**13** was obtained in an optical purity of 89.5%, but the reaction was by ca. 1 order of magnitude slower.

The ligands (*R*)-(*S*)-**3c** and the known (*S*)-(*R*)-**3b**[6] were also used in the catalytic allylic alkylation of **12**. As shown in Scheme 5, significantly lower selectivities were obtained under the same conditions (66 and 81% ee, respectively). Furthermore, both ligands gave catalyst activities about 1 order of magnitude lower than those obtained with **3a**. We interpret these results as follows: whereas the lower activity found in the case of **3c** could be explained on the basis of the enhanced steric hindrance of the *tert*-butyl groups, this argument cannot be applied to **3b**. Rather, the modest results afforded by this latter ligand are due to the electronic similarity of the two phosphino fragments. Thus for this particular reaction, the combination of diphenyl- and dicyclohexylphosphino fragments in **3a** ensures the so far best control of stereoselectivity, because both the steric and electronic features of this ligand are acting in a cooperative manner.

(16) For reviews, see, e.g.: (a) Trost, B. M.; Verhoeven, T. R. In *Comprehensive Organometallic Chemistry*; Wilkinson, G., Stone, F. G. A., Abel, E. W., Eds.; Pergamon Press: Oxford, 1982; Vol. 8, pp 799–938. (b) Consiglio, G.; Waymouth, R. M. *Chem. Rev.* 1989, *89*, 257–276. (c) Hayashi, T. In *Catalytic Asymmetric Synthesis*; Ojima, I., Ed.; VCH Publishers: New York, 1993; pp 325–365. For recent developments, see, e.g. (d) von Matt, P.; Pfaltz, A. *Angew. Chem., Int. Ed. Engl.* **1993**, *32*, 566–568, and references cited therein.

(17) See *inter alia*: Hayashi, T.; Yamamoto, A.; Hagihara, T.; Ito, Y. *Tetrahedron Lett.* **1986**, *27*, 191–194.

**Scheme 5**




## Conclusions

Compounds **3a–c** are representatives of a series of easily accessible chiral chelating ligands in which the two phosphino groups can be introduced independently from one another in two consecutive synthetic steps. Such a two-step preparation warrants a great flexibility, and the approach should allow a fine-tuning of the ligands, *both with respect to their steric and electronic properties*.[18] Work directed toward the extension of the series of different ligands of type **3**, their complexes (including X-ray structural characterization), and further applications in homogeneous asymmetric catalysis, including mechanistic studies, is in progress and will be reported in due course.

## Experimental Section

**General Considerations.** All reactions with air- or moisture sensitive materials were carried out under Ar using standard Schlenk techniques. Freshly distilled solvents were used throughout. Routine $^1H$ NMR (250.133 MHz) and $^{31}P$ NMR (101.256 MHz) spectra were recorded with a Bruker AC 250 spectrometer. Chemical shifts are given in ppm relative to internal TMS and to external 85% $H_3PO_4$, respectively, and coupling constants (*J*) are given in Hz. Optical rotations were measured with a Perkin-Elmer 241 polarimeter using 10-cm cells. Low-resolution EI/MS spectra were recorded at 70 eV on a Finnigan MAT 212/SS300 spectrometer. Merck silica gel 60, 70–230, or 230–400 mesh ASTM was used for flash column chromatography. Thin-layer chromatography (TLC) was performed with Macherey-Nagel Polygram SIL G/UV254 precoated plastic sheets. Elemental analyses were done by Analytical Research Services, Ciba-Geigy Ltd. Capillary GC analyses were done on a Carlo Erba/Fisons Instruments GC 8000 series chomatograph (FID detection) equipped with a DP 700 data processor. Macherey-Nagel 50 m × 0.32 mm ID Permabond L-Chirasil-Val and 50 m × 0.25 mm ID FS Lipodex E columns were used. HPLC analyses were carried out with a Hewlett-Packard 1050 series instrument equipped with a 25 cm Daicel Chiralcel ODH column (254-nm detection) and hexane/2-propanol mixtures as eluent.

**(*R*)-1-[(*S*)-2-(Diphenylphosphino)ferrocenyl]ethyldicyclohexylphosphine ((*R*)-(*S*)-3a).** *N,N*-Dimethyl-(*R*)-1-[(*S*)-2-(diphenylphosphino)ferrocenyl]ethylamine ((*R*)-(*S*)-**1**) (7.94 g, 18.0 mmol) was suspended in 150 mL of anhydrous and degassed acetic acid, under an argon atmosphere. After the addition of 4.1 mL (20.4 mmol) of dicyclohexylphosphine (obtained from Strem Chemicals, Inc., and used without further purification), the mixture was stirred at 80 °C for 3.5 h. The solvent was then evaporated *in vacuo* at ca. 70 °C, and the residue was dissolved in 200 mL of refluxing ethanol. Upon cooling to room temperature, the microcrystals of the product which formed (8.99 g) were filtered off, washed with small portions of cold ethanol, and recrystallized from the same solvent, affording 8.49 g of **3**. From the mother liquors of both crystallization two other crops of product (0.47 and 0.51 g, respectively) could be obtained upon concentration to about 1/10 of the original volume: total yield 9.47 g (88.5%). $[\alpha]^{22}_D = -346$ (*c* 0.6, $CHCl_3$); TLC (hexane/EtOAc, 3:1 volume) $R_f$ 0.68; $^1H$ NMR (259 MHz, $CDCl_3$) δ 0.92–1.22 (br m, 11 Cy H), 1.34–1.72 (br m, 11

(18) This approach is not completely new but has not yet been exploited in a systematic way. To our knowlwedge, the only relevant example is due to Achiwa. See: Inoguchi, K.; Sakuraba, S.; Achiwa, K. *Synlett* **1992**, 169–178, and references cited therein.

**Table 1.** Experimental Details for the Chromatographic Determination of Optical Purities

| compd | column[a] | conditions | retention times[b] (min) *R*-enantiomer | *S*-enantiomer |
|---|---|---|---|---|
| **5a** | GC L-Chirasil-Val | $T$ = 150 °C, isothermic, 120 kPa He carrier, on column injection | 31.50 | 30.97 |
| **5c** | GC L-Chirasil-Val | $T$ = 130 °C, isothermic, 150 kPa He carrier, split 2:20 | 5.30 | 5.60 |
| **7** | GC FS-Lipodex-E | $T$ = 100 °C, isothermic, 120 kPa $H_2$ carrier, split 1:50 | 9.93 | 9.67 |
| **9a**[c] | GC FS-Lipodex-E | $T$ = 40 °C, 5 min, then 2°/min up to 180 °C, 200 kPa $H_2$ carrier, split 2:20 | 29.2 | 28.5 |
| **9b**[d] | GC L-Chirasil-Val | $T$ = 130 °C, isothermic, 150 kPa He carrier, split 2:20 | 12.20 | 12.76 |
| **11a** | HPLC Chiralcel ODH | $T$ = 25 °C, hexane/*i*-PrOH 90:10 flow 0.5 mL/min | 11.33 | 12.39 |
| **11b** | HPLC Chiralcel ODH | $T$ = 25 °C, hexane/*i*-PrOH 90:10 flow 0.5 mL/min | 12.87 | 11.99 |
| **13** | HPLC Chiralcel ODH | $T$ = 25 °C, hexane/*i*-PrOH 98:2 flow 0.5 mL/min | 19.60 | 20.64 |

[a] See General Considerations. [b] Time at maximum peak height for baseline separated peaks. Note that the GC retention times for the same compound can significantly vary depending on the different sources (manufacturers) of the column, even for identical specifications. [c] After derivatization with trifluoroacetic anhydride. [d] After derivatization with isopropyl isocyanate.

Cy H), 1.54 (dd, $J$ = 7, 3, 3H), 3.13 (qd, $J$ = 2, 2, 1H), 3.77 (s, 5 Cp H), 3.93–3.97 (m, 1 Cp H), 4.20–4.25 (m, 1 Cp H), 4.28–4.33 (m, 1 Cp H), 7.07–7.18 (m, 5 Ph H), 7.26–7.34 (m, 3 Ph H), 7.54–7.62 (m, 2 Ph H); $^{31}$P NMR (101 MHz, $CDCl_3$) $\delta$ +15.7 (d, $J_{PP}$ = 30, $PCy_2$), −25.8 (d, $PPh_2$); MS *m/z* 594 ($M^+$), 511, 397, 212. Anal. Calcd for $C_{36}H_{44}P_2Fe$: C, 72.73; H, 7.46; P, 10.42. Found: C, 72.50; H, 7.58; P, 10.51.

**(*S*)-1-[(*R*)-2-(Diphenylphosphino)ferrocenyl]ethyldiphenylphosphine ((*S*)-(*R*)-3b).** This compound was obtained similarly to the one described above from 1.5 g (3.40 mmol) of *N,N*-dimethyl-(*S*)-1-[(*R*)-2-(diphenylphosphino)ferrocenyl]ethylamine ((*S*)-(*R*)-**1**) and 0.6 mL (3.46 mmol) of dicyclohexylphosphine (obtained from Strem Chemicals, Inc. and used without further purification) in 20 mL of acetic acid at 120 °C for 1 h, in 80% yield: $[\alpha]^{22}_D$ = +355 ($c$ = 1.0, $CHCl_3$); TLC (hexane/EtOAc, 3:1 volume) $R_f$ 0.56; $^1$H NMR (250 MHz, $CDCl_3$) $\delta$ 1.58 (dd, $J$ = 7, 7, 3H), 3.95 (qd, $J$ = 2, 2, 1H), 3.96 (s, partially overlapping with previous qd, 5 Cp H), 4.12 (m, 1 Cp H), 4.18 (m, 1 Cp H), 4.34 (t, $J$ = 2.5, 1 Cp H), 7.20–7.53 (m, 16 Ph H), 7.74–7.85 (m, 4 Ph H); $^{31}$P NMR (101 MHz, $CDCl_3$) $\delta$ +5.9 (d, $J_{PP}$ = 20.6, $CHPPh_2$), −25.8 (d, $CpPPh_2$); MS *m/z* 582 ($M^+$), 505, 397, 320, 212. Anal. Calcd for $C_{36}H_{32}P_2Fe$: C, 74.24; H, 5.54; P, 10.64. Found: C, 74.05; H, 5.53; P, 10.75.

**(*R*)-1-[(*S*)-2-(Diphenylphosphino)ferrocenyl]ethyldi-*tert*-butylphosphine ((*R*)-(*S*)-3c).** This compound was obtained similarly to the one described above from 3.9 g (8.8 mmol) of *N,N*-dimethyl-(*R*)-1-[(*S*)-2-(diphenylphosphino)ferrocenyl]ethylamine ((*R*)-(*S*)-**1**) and 1.64 mL (9.0 mmol) of di-*tert*-butylphosphine (obtained from the $LiAlH_4$ reduction of di-*tert*-butylchlorophosphine, available from Strem Chemicals, Inc.) in 75 mL of acetic acid at 80 °C for 3 h, in 81% yield: $[\alpha]^{22}_D$ = −417 ($c$ 0.6, $CHCl_3$); TLC (hexane/EtOAc, 3:1 volume) $R_f$ 0.63; $^1$H NMR (250 MHz, $CDCl_3$) $\delta$ 0.92 (d, $J$ = 7, 9H), 1.12 (d, $J$ = 7, 9H), 1.78 (dd, $J$ = 7, 3, 3H), 3.37 (qd, $J$ = 7, 2, 1H), 3.77 (s, 5 Cp H), 3.90–3.95 (m, 1 Cp H), 4.14–4.18 (m, 1 Cp H), 4.29–4.33 (m, 1 Cp H), 7.06–7.21 (m, 5 Ph H), 7.25–7.33 (m, 3 Ph H), 7.52–7.62 (m, 2 Ph H); $^{31}$P NMR (101 MHz, $CDCl_3$) $\delta$ +49.9 (d, $J_{PP}$ = 50, $P(t\text{-}Bu)_2$), −26.1 (d, $PPh_2$); MS *m/z* 542 ($M^+$), 517, 485, 429, 397, 243, 212. Anal. Calcd for $C_{32}H_{40}P_2Fe$: C, 70.85; H, 7.43; P, 11.42. Found: C, 70.76; H, 7.37; P, 11.48.

**Enantioselective Hydrogenation Reactions.** The procedures are exemplified by the hydrogenation of dimethyl itaconate (**6**). Ligand (*R*)-(*S*)-**3a** (20.5 mg, 0.034 mmol) was added to a solution of 11.8 mg of $[Rh(NBD)_2]BF_4$ (0.031 mmol) in 10 mL of methanol, and the solution was stirred for 15 min. It was then transferred via a steel capillary into a 180-mL glass reactor equipped with a cooling jacket. A solution of 0.9 g of dimethyl itaconate (3.1 mmol) in 5 mL of methanol was transferred into the reactor in a similar manner. The inert gas was then replaced by hydrogen (three cycles), and the pressure was set at 1.08 bar. After completion of the reaction (no further hydrogen takeup after 20 min) the conversion was determined gas chromatographically (quantitative), and the product was isolated in ca. 100% yield after filtration of the reaction solution on a plug of silica (removal of the catalyst). The optical yield was determined by NMR using the paramagnetic shift reagent [Eu(hfbc)$_3$] (>96% ee) and by GC (FS Lipodex E column, 98.5% ee, see Table 1). The absolute configuration was assigned on the basis of the relative GC retention time, compared with that of an authentic sample of commercially available (*R*)-**7**.

An analogous procedure was followed for the hydrogenation of methyl acetamidocinnamate (**4a**) and methyl acetamidoacrylate (**4c**). The optical purity of the hydrogenation products (*S*)-**5a** and -**5c**, respectively, was determined by GC (L-Chirasil-Val column, see Table 1). Assignment of the absolute configuration was made by comparison of the optical rotations with that of authentic samples. The hydrogenation of acetamidocinnamic acid (**4b**) was carried out in ethanol at 5 °C with 1 mol % of catalyst and the optical purity of the product, obtained in quantitative yield, was determined by GC after conversion to the methyl ester (*S*)-**5a**.

The hydrogenation of methyl and ethyl 3-oxobutyrate, **8a** and **8b**, respectively, was carried out in a 50 mL steel autoclave under a hydrogen pressure of 20 bar, using methanol as solvent, and a substrate to catalyst ratio of 100/1. The products were isolated in essentially quantitative yield after a reaction time of 15 h. Determination of optical purities was carried out by GC after derivatization with trifluoroacetic anhydride (**9a**, Lipodex E column) and with isopropyl isocyanate (**9b**, L-Chirasil-Val column), respectively.

**Enantioselective Allylic Alkylation Reactions.** The procedures are exemplified by the experiments carried out with ligand **3a**. The ligand (*R*)-(*S*)-**3a** (7.6 mg 0.0128 mmol) was dissolved in 5 mL of freshly distilled $CH_2Cl_2$ under an argon atmosphere. To the yellow solution 2.3 mg of $[Pd_2(\eta^3\text{-}C_3H_5)_2Cl_2]$ (0.0064 mmol) was added. After 10 min the color of the solution turned from yellow to dark orange. Racemic 1,3-diphenyl-1-acetoxypropene (323 mg, 1.28 mmol), *N,O*-bis(trimethylsilyl)acetamide (0.626 mL, 2.56 mmol), dimethyl malonate (0.293 mL, 2.56 mmol), and potassium acetate (6 mg, 0.06 mmol) were added in this order. The reaction was monitored by TLC (eluent: ethyl acetate/hexane 1:5 volume; product **13a**: $R_f$ 0.37). After 3 h (no starting material **12a** could be detected after 2 h) the orange slurry was filtered, and about two-thirds of the solvent was removed *in vacuo*. Column chromatography on silica gel, using the same eluent as for TLC, yielded 410 mg (1.27 mmol, 99%) of (*S*)-**13a** as a colorless oil that solidified upon standing in the cold. The optical purity was determined to be 93% by HPLC (Daicel Chiralcel ODH column, see Table 1). This result was confirmed by NMR using the paramagnetic shift reagent [Eu(hfbc)$_3$]. Assignment of the absolute configuration was made by the sign of the optical rotation.[15d] *Care must be exercized using the HPLC method, since nearly racemic product* ***13*** *tends to precipitate from hexane solutions, used as samples, thus incidentally affording higher ee's than the actual ones. This spontaneous optical enrichment was not observed when sample concentrations ≤5 mg/mL were used.*

**Enantioselective Hydroboration Reactions.** The protocol is exemplified by the procedure for the hydroboration of styrene. A mixture of 15 mg of $[Rh(NBD)_2]BF_4$ (0.04 mmol) and 26.2 mg of the ligand (*R*)-(*S*)-**3** (0.044 mmol) in 2 mL of dry dimethoxyethane was stirred at 25 °C for 30 min, after which 0.23 mL of styrene (2 mmol) was added. 0.227 mL of catecholborane (2.2 mmol) was added at −70 °C and the mixture was stirred at the same temperature for 9 h. The reaction was then quenched by the addition of methanol (4 mL). Aqueous NaOH (4.8 mL, 3 M) and 0.41 mL of 35% aqueous $H_2O_2$ (4.4 mmol) were added subsequently,

and the mixture was allowed to warm to room temperature over a period of 3 h under vigorous stirring. The mixture was then extracted with three 20-mL portions of diethyl ether. The organic phase was washed with two portions of 1 M aqueous NaOH and saturated aqueous $NH_4Cl$, respectively, dried over $MgSO_4$, and concentrated in vacuo. Column chromatography of the residue on silica gel (eluent: hexane/diethyl ether 1:1 volume) gave the pure product in 65% yield.

The optical purity of **11a** was determined to be 91.5% by HPLC (Daicel Chiralcel ODH column, see Table 1), and the absolute configuration was assigned on the basis of the sign of the optical rotation.[14d]

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