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Synthesis of Exclusively Centrostereogenic 1,3-Bidentate Ferrocenyldiphosphane Ligands and Their Use in Enantioselective Hydrogenations

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Five representatives of a novel class of 1,3-bidentate and exclusively centrostereogenic ferrocenyldiphosphane ligands were prepared from ferrocene in a five-step sequence. The ligands were tested in rhodium-mediated asymmetric hydrogenations of two alkenes (methyl acetamidocinnamate and dimethyl itaconate) and delivered high product enantioselectivities of up to 96% ee. The coordination behavior of one ligand in its square-planar palladium dichloride complex was studied by X-ray diffraction, and the *R* absolute configuration was determined from the X-ray anomalous dispersion effects.

Introduction

Chiral nonracemic ferrocenyldiphosphanes have been widely used as ligands for enantioselective transition-metal catalysts that have a broad range of applications in asymmetric transformations.[1] In particular, ruthenium, rhodium, and iridium complexes of diphosphanes such as Josiphos-, Taniaphos-, or Walphos-type ligands (Chart 1) were found to give excellent results in enantioselective hydrogenations[2] and this has led to the development of a number of industrial hydrogenation processes.[3]

From a structural point of view, the majority of all ferrocenyldiphosphanes applied in enantioselective catalysis are based on a stereogenic (planar chiral) 1,2-disubstituted ferrocene backbone[1,4] and this fact is considered to contribute significantly to their excellent performance. However, planar stereogenicity is not a general requirement for a ligand to induce high product enantioselectivity,and we therefore questioned whether ferrocene-based ligands lacking this type of stereogenicity could perform as well as, for example, Josiphos,[5] Taniaphos,[6] Walphos,[7] or similar ligands.[8]

For this purpose we explored the exclusively centrostereogenic 1,3-bidentate ligands of type **1** (Chart 1). Unlike the Taniaphos-type ligands,[9,6] in these newly developed ligands the ferrocene unit is considered to be a sterically demanding substituent rather than a part of the ligand backbone. In this contribution we report on the synthesis of ligands of type **1** and describe their performance in the rhodium-catalyzed enantioselective hydrogenations of two alkenes. In addition, the structural features of a palladium dichloride complex of one representative ligand are discussed.

Results and Discussion

Synthesis of Ligands 1a−e. The synthesis of ligands **1a−e** started from alcohol (*R*)-**4**, which was accessible in 95% yield and 96% ee by Corey−Bakshi−Shibata (CBS) reduction of (2-bromobenzoyl)ferrocene (**2**).[9c] For this reaction (*S*)-α,α-oxazaborolidine **3** was used as the catalyst (Scheme 1). After recrystallization from heptane (*R*)-**4** was obtained in >99% ee. The molecular structure of (*R*)-**4** was determined by X-ray

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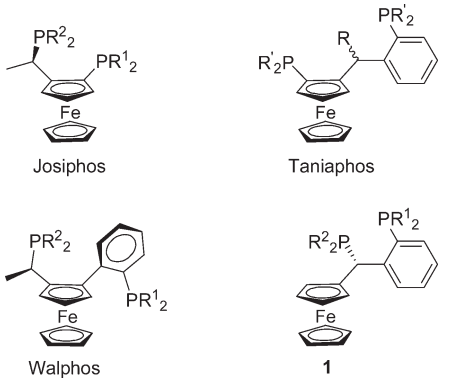
diffraction, and the absolute *R* configuration was deduced from the X-ray anomalous dispersion effects and was consistent with the chemical evidence (Figure 1). Reaction of alcohol (*R*)-**4** with methanol in the presence of acetic acid gave the methyl ether (*R*)-**5** in 99% yield and 99% ee. In a subsequent step the bromo substituent of (*R*)-**5** was exchanged with lithium and the lithiated intermediate was then reacted with chlorodiphenylphosphane. This reaction gave monophosphane (*R*)-**6a** in 95% yield and 98% ee. It is worth mentioning that racemization at the stereogenic center did not occur under the reaction conditions used for the bromo/lithium exchange. On using the same reaction conditions and chlorodi-2-furylphosphane as the electrophile, phosphane (*R*)-**6b** was obtained from (*R*)-**5** (75% yield, 97% ee). In the final step, treatment of (*R*)-**6a** with diphenylphosphane in acetic acid at 65 °C gave the 1,3-bidentate diphosphane (*R*)-**1a** in 90% yield and 97% enantiomeric excess and, after recrystallization from methanol, this could be increased to >99% ee. In a way similar to that for **1a**, diphosphanes (*R*)-**1b** and (*R*)-**1c** were obtained from the precursor (*R*)-**6a** on using dicyclohexylphosphane and di-2-furylphosphane as the nucleophiles, respectively, in 72% and 79% yield. Similarly, (*R*)-**1d** and (*R*)-**1e** were prepared from (*R*)-**6b** (**1d**, 74% yield, 97% ee; **1e**, 78% yield).

On the basis of the known *R* absolute configuration of alcohol **4** and the reaction conditions used for the subsequent transformations **4** → **5** → **6a**, it seemed plausible to assume retention of configuration at the stereogenic center for each step. As a result, an *R* absolute configuration for products **5** and **6a** seems reasonable (otherwise, for either of these reaction steps only clean inversion at the stereogenic center could explain the high product enantiomeric excess obtained in both transformations). In analogy to previous work[5,10] the methoxy/phosphane exchange (transformation **6** → **1**) is also expected to proceed with retention of configuration at the stereogenic center, a fact that again should lead to products with an *R* absolute configuration. In the case of derivative **1a** the *R* absolute configuration was confirmed by an X-ray diffraction study on the palladium dichloride complex [$PdCl_2$(**1a**)].

Synthesis and Molecular Structure of Complex [$PdCl_2$((*R*)-1a)]. In order to study the coordination behavior of ligands of type **1** and to determine their absolute configuration, the palladium complex [$PdCl_2$(**1a**)] was prepared by reacting a sample of **1a** with [$PdCl_2(CH_3CN)_2$] (Scheme 2). Single crystals of this complex were grown, and the molecular structure was studied by X-ray diffraction. Furthermore, the absolute *R* configuration was determined from the X-ray anomalous dispersion effects. Details of the X-ray crystallographic data are given in the Experimental Section. A view of the molecular structure of [$PdCl_2$((*R*)-**1a**)] is given in Figure 2.

In the solid state ligand **1a** coordinates in a bidentate fashion to palladium, forming a six-membered chelate ring

Chart 1



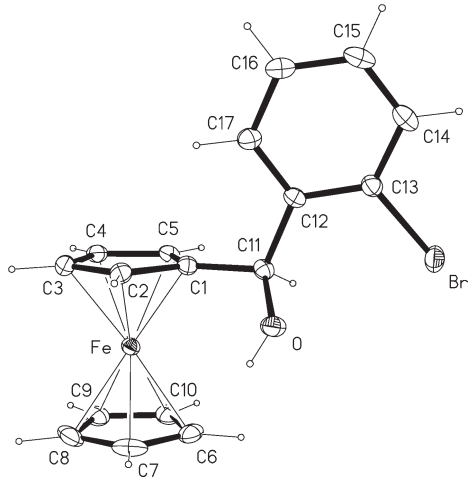
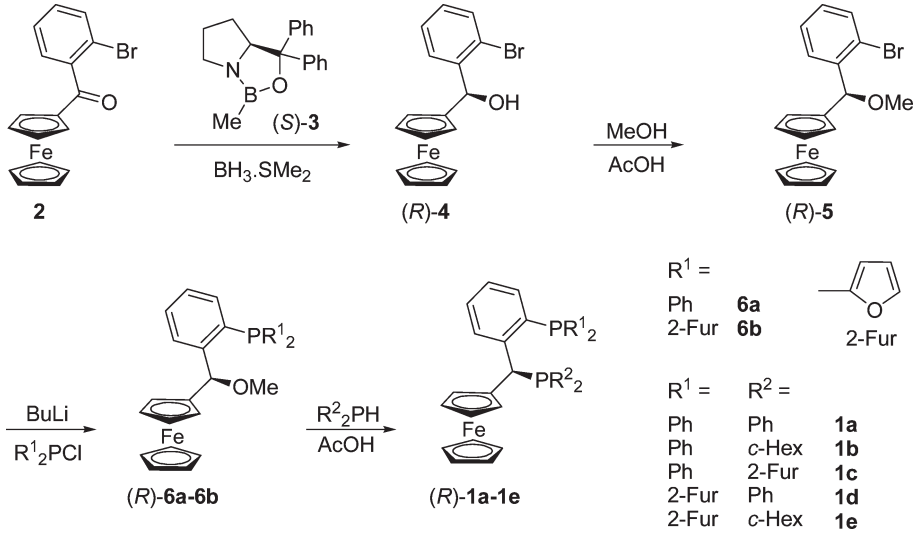


Figure 1. Molecular structure and absolute configuration of (*R*)-**4**.

Scheme 1. Synthesis of Ligands 1a−e



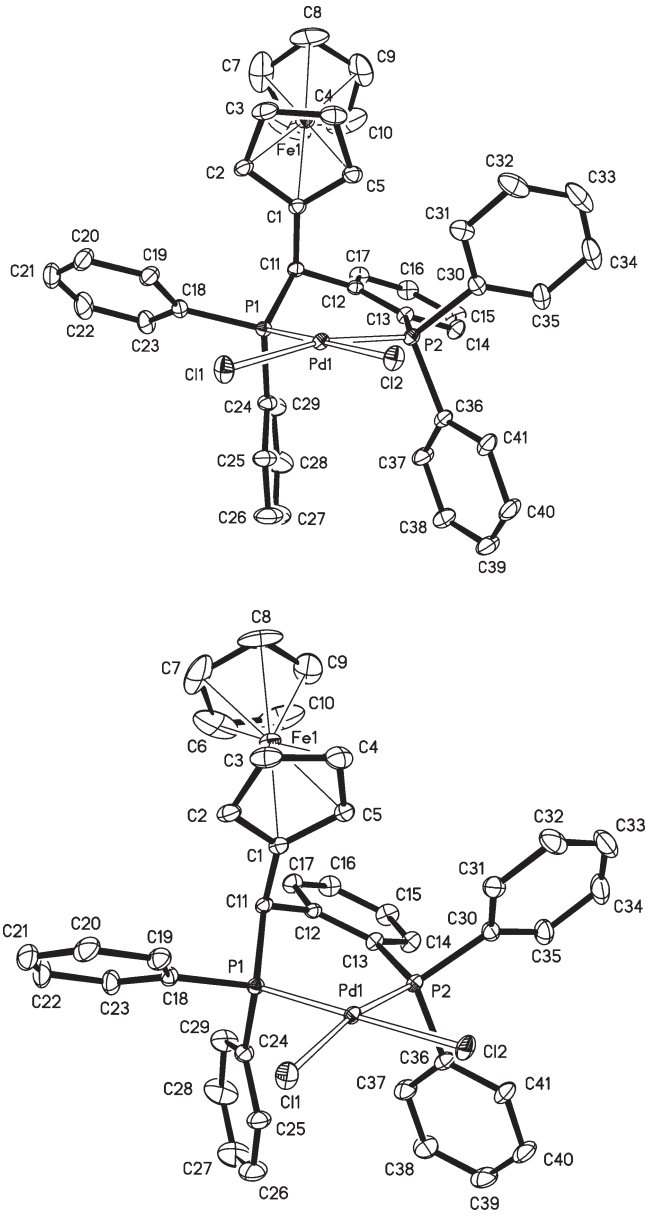
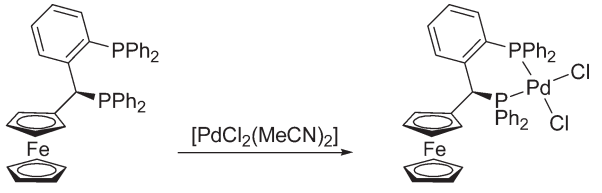


Figure 2. Molecular structure of $[PdCl_2(R)\text{-}\mathbf{1a}]$ in $[PdCl_2(R)\text{-}\mathbf{1a}]\cdot 3CHCl_3$ (H atoms and $CHCl_3$ omitted for clarity).

Scheme 2. Synthesis of $[PdCl_2((R)\text{-}\mathbf{1a})]$



(*R*)-**1a** $[PdCl_2((R)\text{-}\mathbf{1a})]$

with a twisted half-chair conformation (P1 in an apical position and 0.86 Å above the least-squares plane C11−C12−C13−P2−Pd1; Figure 2). Interestingly, the ferrocene unit is attached to this ring in a pseudo-axial rather than in a pseudo-equatorial position. The palladium atom is located in a square-planar environment that deviates slightly from planarity (for P1−P2−Cl1−Cl2 the rms deviation from planarity is 0.091 Å). In the solid state this square-planar unit is embedded in a chiral pocket formed by the four phosphorus-bound phenyl rings and one cyclopentadienyl ring. We have evidence that the complex exhibits considerable flexibility via changes in chelate ring conformation and orientations of phenyl and ferrocene moieties, factors that are considered important for a good catalytic performance.

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Scheme 3. Asymmetric Test Hydrogenations with Ligands 1a−e

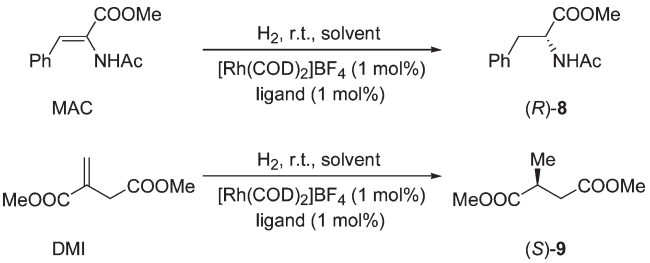

Table 1. Results Obtained in the Hydrogenation of MAC and DMI with Ligands (*R*)-1a−e

entry	substrate	ligand	solvent	pH_2 (bar)	*t* (h)	yield (%)	ee (%)[a]
1	MAC	**1a**	MeOH	1	3	quant	80 (*R*)
2	MAC	**1a**	CH_2Cl_2	1	3	quant	81 (*R*)
3	MAC	**1a**	acetone	1	3	quant	81 (*R*)
4	MAC	**1a**	MeOH/toluene	1	3	quant	85 (*R*)
5	MAC	**1b**	MeOH/toluene	1	3	quant	64 (*R*)
6	MAC	**1c**	MeOH/toluene	1	3	quant	69 (*R*)
7	MAC	**1d**	MeOH/toluene	1	3	quant	92 (*R*)
8	MAC	**1e**	MeOH/toluene	1	3	quant	94 (*R*)
9	DMI	**1a**	MeOH	1	20	0	
10	DMI	**1a**	MeOH/toluene	1	20	<2	nd
11	DMI	**1a**	MeOH	10	16	quant	92 (*S*)
12	DMI	**1a**	THF	1	5	quant	75 (*S*)
13	DMI	**1a**	CH_2Cl_2	1	3	quant	95 (*S*)
14	DMI	**1b**	CH_2Cl_2	1	3	quant	86 (*S*)
15	DMI	**1c**	CH_2Cl_2	1	3	quant	80 (*S*)
16	DMI	**1d**	CH_2Cl_2	1	2	quant	94 (*S*)
17	DMI	**1e**	CH_2Cl_2	1	3	quant	96 (*S*)

[a] The product enantiomeric excess was determined by GC (Chiralsil-*L*-Val; MAC) or HPLC (Chiralcel OD; DMI). Product absolute configurations were determined by comparison of relative retention times with literature data.

Enantioselective Hydrogenations. All diphosphanes (*R*)-**1a−e** were tested in rhodium-mediated asymmetric hydrogenations of methyl acetamidocinnamate (MAC) and dimethyl itaconate (DMI). All catalysts were formed in situ by reacting the ligands with $[Rh(COD)_2]BF_4$. Standard test reaction conditions were used (see the Experimental Section), and the results obtained in the hydrogenation of substrates MAC and DMI (Scheme 3) are given in Table 1.

The hydrogenation of MAC required only very mild reaction conditions. Quantitative conversion was achieved in each case within 3 h at room temperature and with a hydrogen pressure of 1 bar. The influence of solvents on the hydrogenation results was tested with ligand **1a** and was found to be rather small. Neither the conversion nor the product enantiomeric excess changed significantly on changing the polarity of the solvent (Table 1, entries 1−4). The best results were obtained on using a mixture of methanol and toluene in a ratio of 9:1 (entry 4, 85% ee). Variation of the phosphane substituents showed different trends. When the diphenylphosphanyl substituent at the stereogenic

center was replaced by either a dicyclohexyl or a di-2-furylphosphanyl residue, the product enantiomeric excess dropped to 64% ee (**1b**) and 69% ee (**1c**) (entries 5 and 6). When the diphenylphosphanyl unit at the backbone phenyl ring was replaced by a di-2-furylphosphanyl unit, the ee values increased to 92% (**1d**) and 94% (**1e**), respectively (entries 7 and 8).

Interestingly, in contrast to the results obtained with the substrate MAC, the hydrogenation of DMI proved to be strongly dependent on the solvent used (Table 1, entries 9−12). For example, on using ligand **1a** with either methanol or a methanol/toluene mixture (9:1) as the solvent and a hydrogen pressure of 1 bar, hardly any conversion was observed even with a prolonged reaction time of 20 h. Only when the hydrogen pressure was increased to 10 bar was quantitative conversion and a product enentioselectivity of 92% obtained, and this was after a reaction time of 16 h (entry 11). However, when methanol was replaced by dichloromethane, the reactions only required a hydrogen pressure of 1 bar and quantitative conversion was achieved within 2−3 h. The use of ligands **1a**,**d**,**e** led to products with 95%, 94%, and 96% ee (entries 13, 16, and 17), while with ligands **1b**,**c** the enantioselectivity dropped significantly to 86% and 80%, respectively (entries 14 and 15).

Summary

Exclusively centrostereogenic ligands **1a**−**e** were prepared in a five-step sequence from ferrocene. All ligands were tested in rhodium-mediated asymmetric hydrogenations of methyl acetamidocinnamate (MAC) and dimethyl itaconate (DMI). In both cases mild reaction conditions led to quantitative conversion and product enantioselectivities of up to 94% (MAC) and 96% ee (DMI). These values compare very well with those obtained on using typical ferrocene stereogenic ligands such as Josiphos and Taniaphos or similar ferrocene derivatives.

Experimental Section

General Considerations. NMR spectra were recorded on Bruker DPX-400 and AC-300 spectrometers in $CDCl_3$ or DMSO-d_6. Chemical shifts (δ) are given relative to $CHCl_3$ (^{1}H, 7.24 ppm), $CDCl_3$ (^{13}C, 77.0 ppm), DMSO (^{1}H, 2.50 ppm), DMSO-d_6 (^{13}C, 39.5 ppm), and 85% H_3PO_4 (^{31}P, 0 ppm). The coupling constants in $^{13}C\{^1H\}$ spectra are due to $^{13}C-^{31}P$ coupling. For signal assignment the following terms were used: s, bs, d, dd, t, q, and m refer to singlet, broad singlet, doublet, doublet of doublets, triplet, quartet, and multiplet, respectively. Melting points were determined either on a Kofler melting point apparatus or on a Büchi B 450 apparatus and are uncorrected. Mass spectra were recorded on Finnigan MAT 900 or MAT 95 or Varian MAT CH 7A or MAT 711 spectrometers. Optical rotations were measured on a Perkin-Elmer 241 polarimeter. Elemental analyses were carried out on a Heraeus CHN-Rapid Elemental analyzer at the Department of Chemistry of the Ludwig-Maximilians-University Munich. HPLC was performed in an isocratic mode on Dionex systems with Daicel Chiralcel OD and AD columns and mixtures of *n*-heptane and 2-propanol. All reactions required inert conditions and were carried out under an argon atmosphere using standard Schlenk techniques. All solvents were dried by standard procedures and distilled before use. Chromatographic separations were performed under gravity on silica (Merck, 40−63 μm). DEE denotes diethyl ether.

(*R*)-[Methoxy(2-bromophenyl)methyl]ferrocene ((*R*)-5). Alcohol (*R*)-**4**[9c] (2.40 g, 6.46 mmol) was dissolved in methanol (100 mL), and acetic acid (4 mL) was added. The resulting mixture was stirred at room temperature for 16 h followed by removal of the solvents under reduced pressure. The remaining residue was taken up in DEE and washed with saturated aqueous potassium carbonate and brine. After drying over $MgSO_4$ the solvent was removed on a rotary evaporator and the crude product was purified by recrystallization from methanol to give the product as an orange solid (2.46 g, 99% yield, 99% ee). In an analogous manner a racemic sample of **5** was obtained as an orange solid. Mp: 80 °C. $[\alpha]_D^{20} = -52.4°$ (*c* 0.58, $CHCl_3$). ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.47−7.42 (m, 2 H), 7.28−7.18 (m, 1 H), 7.07−6.96 (m, 1 H), 5.42 (s, 1 H), 4.16−4.13 (m, 2 H), 4.05 (s, 5 H), 4.02−3.96 (m, 2 H), 3.20 (s, 3 H). $^{13}C\{^1H\}$ NMR (75 MHz, $CDCl_3$): δ 141.4, 132.4, 128.8, 128.4, 127.6, 123.5, 89.9, 80.1, 68.7, 67.7, 67.3, 67.2, 66.3, 56.9. MS (EI): *m*/*z* 386 (M + 1, 54), 385 (M^+, 12), 384 (M − 1, 49), 152 (100), 122 (35). Anal. Calcd for $C_{18}H_{17}BrFeO$ (385.08): C, 56.14; H, 4.45. Found: C, 55.84; H, 4.54. HPLC (OD, 5% *i*-PrOH, 0.6 mL/min, 254 nm): t_r/min = 7.9 (*R*), 14.1 (*S*).

General Procedure 1. Derivative **5** (2.60 mmol) was dissolved in THF (30 mL) and cooled to −78 °C. A solution of *n*-BuLi in hexane (1.5 M, 2.86 mmol, 1.1 equiv) was added dropwise with stirring. After complete addition stirring was continued for 15 min followed by dropwise addition of the electrophile (3.12 mmol, 1.2 equiv). The reaction mixture was warmed to room temperature, stirred for an appropriate time, quenched by the addition of water, and extracted with DEE. The combined organic layers were washed with brine and dried over $MgSO_4$, and the solvent was removed on a rotary evaporator. The crude product was purified by chromatography on silica.

(*R*)-[Methoxy(2-(diphenylphosphanyl)phenyl)methyl]ferrocene ((*R*)-6a). According to general procedure 1 bromide (*R*)-**5** (2.03 g, 5.28 mmol) was reacted with *n*-BuLi in hexane (1.5 M, 3.87 mL, 5.81 mmol, 1.1 equiv) and subsequently with chlorodiphenylphosphane (1.14 mL, 6.34 mmol, 1.2 equiv) in THF (60 mL). After addition of the electrophile stirring was continued for 45 min at room temperature. Chromatography with pentane/DEE (20/1) as the eluent gave the desired product as a yellow solid (2.46 g, 95% yield, 98% ee). A racemic sample of **6a** was prepared in an analogous manner and was isolated as an orange solid. Mp: 101 °C. $[\alpha]_D^{20} = +52.8°$ (*c* 0.86, $CHCl_3$). ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.43−7.39 (m, 1 H), 7.28−7.20 (m, 11 H), 7.09−7.03 (m, 1 H), 6.88−6.84 (m, 1 H), 5.94 (d, *J* = 7.7 Hz, 1 H), 4.21−4.21 (m, 1 H), 4.02, (s, 5 H), 3.97−3.96 (m, 1 H), 3.89−3.88 (m, 1 H), 3.77−3.76 (m, 1 H), 3.07 (s, 3 H). $^{13}C\{^1H\}$ NMR (75 MHz, $CDCl_3$): δ 147.6 (d, *J* = 23.3 Hz), 137.1 (d, *J* = 10.5 Hz), 136.5 (d, *J* = 10.7 Hz), 135.2 (d, *J* = 14.4 Hz), 134.2−127.3 (m), 91.3, 78.3 (d, *J* = 26.2 Hz), 68.8, 67.5, 66.9, 66.7, 56.7. $^{31}P\{^1H\}$ NMR (81 MHz, $CDCl_3$): δ −16.3. MS (EI): *m*/*z* 491 (M + 1, 23), 490 (M^+, 67), 460 (28), 395 (100), 337 (98), 183 (70). HR-MS: *m*/*z* $[M]^+$ calcd 490.1149 for $C_{30}H_{27}FeOP$, found 490.1174. HPLC (OD, 2% *i*-PrOH, 0.6 mL/min, 254 nm): t_r/min = 7.7 (*R*), 8.6 (*S*).

(*R*)-[Methoxy(2-(di-2-furylphosphanyl)phenyl)methyl]ferrocene ((*R*)-6b). According to general procedure 1 bromide (*R*)-**5** (400 mg, 1.04 mmol) was reacted with *n*-BuLi in hexane (1.5 M, 0.76 mL, 1.14 mmol, 1.1 equiv) and chlorodi-2-furylphosphane (251 mg, 1.25 mmol, 1.2 equiv) in THF (60 mL). After addition of the electrophile stirring was continued for 90 min at room temperature. Purification was achieved by chromatography with pentane/DEE (30/1) as the eluent to give the product as an orange-brown oil (367 mg, 75% yield, 97% ee). A racemic sample of **6b** was obtained in an analogous manner as a brown oil. $[\alpha]_D^{20} = +19.0°$ (*c* 0.84, $CHCl_3$). ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.60−7.58 (m, 2 H), 7.43−7.38 (m, 1 H), 7.30−7.25 (m, 2 H), 7.16−7.11 (m, 1 H), 6.62−6.60 (m, 2 H), 6.37−6.34 (m, 2 H), 5.80 (d, *J* = 6.8 Hz, 1 H), 4.14−4.13 (m, 1 H), 4.03 (s, 5 H), 3.98−3.97 (m, 1 H), 3.95−3.94 (m, 1 H), 3.88−3.87 (m, 1 H), 3.07 (s, 3 H). $^{13}C\{^1H\}$ NMR (75 MHz, $CDCl_3$): δ 150.6 (d, *J* = 6.4 Hz), 150.1 (d, *J* = 7.3 Hz), 147.6 (d, *J* = 2.6 Hz), 147.4 (d, *J* = 2.6 Hz), 146.5 (d, *J* = 24.2 Hz), 133.2, 132.3 (d, *J* = 5.3 Hz), 129.8, 127.6, 127.4 (d, *J* = 5.8 Hz), 121.6 (d, *J* = 22.5 Hz), 121.1 (d, *J* = 21.3 Hz), 111.0−110.9 (m), 91.0, 78.5 (d, *J* = 25.1 Hz), 68.8, 67.6, 67.2, 67.1, 66.6 (d, *J* = 2.6 Hz), 56.6. $^{31}P\{^1H\}$ NMR (81 MHz, $CDCl_3$): δ −58.9. MS (EI): *m*/*z* 470 (M^+, 100), 438 (32), 404 (11), 375 (29), 370 (17), 317 (36), 221 (15), 183 (23), 121 (6). HR-MS: *m*/*z* $[M]^+$ calcd 470.0734 for

$C_{26}H_{23}FeO_3P$, found 470.0723. HPLC (OD, 2% *i*-PrOH, 0.6 mL/min, 254 nm): t_r/min = 10.2 (*R*), 12.4 (*S*).

General Procedure 2. Ferrocene **6** was dissolved in degassed acetic acid, and the appropriate phosphane was added dropwise. The mixture was stirred at elevated temperature. The solvent was removed under reduced pressure, and the crude product was redissolved in DEE. The organic phase was washed with saturated aqueous sodium hydrogen carbonate and brine and was dried over $MgSO_4$. The solvent was removed on a rotary evaporator, and the crude product was purified by chromatography on silica.

(*R*)-[Diphenylphosphanyl-(2-(diphenylphosphanyl)phenyl)methyl]-ferrocene ((*R*)-1a). According to general procedure 2 (*R*)-**6a** (700 mg, 1.42 mmol) was reacted with diphenylphosphane (0.30 mL, 1.71 mmol, 1.2 equiv) in acetic acid (10 mL) at 65 °C for 1.5 h. The crude product was purified by chromatography with pentane/DEE (10/1) as the eluent to give the product as an orange solid (0.83 g, 90% yield, 97% ee). A racemic sample of **1a** was obtained as an orange solid. Mp: 137 °C. $[\alpha]_D^{20} = +28.8°$ (*c* 0.74, $CHCl_3$). ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.83−7.78 (m, 2 H), 7.65−7.61 (m, 1 H), 7.41−7.30 (m, 9 H), 7.16−6.92 (m, 9 H), 6.82−6.78 (m, 1 H), 6.59−6.54 (m, 2 H), 6.01 (dd, J = 11.7 Hz, J = 6.5 Hz, 1 H), 3.81−3.77 (m, 3 H), 3.68−3.67 (m, 1 H), 3.43 (s, 5 H). ^{13}C{^{1}H} NMR (75 MHz, $CDCl_3$): δ 148.9 (dd, J = 25.4 Hz, J = 8.2 Hz), 137.7−126.3 (m), 92.0 (d, J = 21.3 Hz), 69.7 (d, J = 9.9 Hz), 68.7 (d, J = 3.2 Hz), 68.6, 66.9, 66.0, 40.8 (dd, J = 30.0 Hz, J = 15.8 Hz). ^{31}P{^{1}H} NMR (81 MHz, $CDCl_3$): δ 7.6 (d, J = 1.9 Hz), −17.7 (d, J = 1.9 Hz). MS (EI): *m*/*z* 645 (M + 1, 9), 644 (M^+, 20), 459 (100), 393 (7), 337 (44), 259 (6), 183 (23), 152 (6), 108 (8), 77 (3). HR-MS: *m*/*z* $[M]^+$ calcd 644.1485 for $C_{41}H_{34}FeP_2$, found 644.1520. HPLC (AD, 2% *i*-PrOH, 0.6 mL/min, 254 nm): t_r/min = 9.3 (*R*), 10.4 (*S*).

(*R*)-[(Dicyclohexylphosphanyl)(2-(diphenylphosphanyl)phenyl)-methyl]ferrocene ((*R*)-1b). According to general procedure 2 (*R*)-**6a** (710 mg, 1.45 mmol) was reacted with dicyclohexylphosphane (0.35 mL, 1.74 mmol, 1.2 equiv) in acetic acid (10 mL) at 65 °C for 1.5 h. The crude product was purified by chromatography with pentane/DEE (10/1) as the eluent to give the desired product as an orange solid (724 mg, 76% yield). A racemic sample of **1b** was isolated as an orange solid. Mp: 103 °C. $[\alpha]_D^{20} = -94.1°$ (*c* 0.75, $CHCl_3$). ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.74−7.70 (m, 1 H), 7.55−7.49 (m, 2 H), 7.36−7.07 (m, 11 H), 5.17 (dd, J = 11.4 Hz, J = 6.6 Hz, 1 H), 4.27 (bs, 1 H), 4.00−3.98 (m, 1 H), 3.85 (bs, 2 H), 3.33 (s, 5 H), 1.74−0.66 (m, 22 H). ^{13}C{^{1}H} NMR (75 MHz, $CDCl_3$): δ 152.4 (dd, J = 26.3 Hz, J = 9.3 Hz), 138.0 (d, J = 10.5 Hz), 137.1 (d, J = 11.6 Hz), 134.9−133.4 (m), 131.0 (dd, J = 12.5 Hz, J = 4.5 Hz), 129.1−128.2 (m), 126.0 (d, J = 1.1 Hz), 94.8 (d, J = 16.9 Hz), 70.6 (d, J = 3.5 Hz), 68.3, 68.0 (d, J = 12.2 Hz), 67.2, 65.1, 36.1 (dd, J = 29.2 Hz, J = 19.3 Hz), 33.9 (d, J = 19.2 Hz), 33.3 (dd, J = 18.7 Hz, J = 2.3 Hz), 31.8 (dd, J = 18.7 Hz, J = 1.1 Hz), 30.2−26.2 (m). ^{31}P{^{1}H} NMR (81 MHz, $CDCl_3$): δ 33.4, −17.7. MS (EI): *m*/*z* 656 (M^+, 2), 574 (39), 573 (100), 459 (18), 393 (4), 337 (11), 305 (2), 259 (3), 183 (5). HR-MS: *m*/*z* $[M]^+$ calcd 656.2424 for $C_{41}H_{46}FeP_2$, found 656.2396.

(*R*)-[(Di-2-furylphosphanyl)(2-(diphenylphosphanyl)phenyl)-methyl]ferrocene ((*R*)-1c). According to general procedure 2 (*R*)-**6a** (405 mg, 0.83 mmol) was reacted with di-2-furylphosphane (206 mg, 1.24 mmol, 1.5 equiv) in acetic acid (6 mL) at 65 °C for 1.5 h. The crude product was purified by chromatography with pentane/DEE (10/1) as the eluent to give the product as an orange solid (408 mg, 79% yield). A racemic sample of **1c** was obtained in an analogous manner as an orange solid. Mp: 65 °C. $[\alpha]_D^{20} = +33.5°$ (*c* 0.86, $CHCl_3$). ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.69−7.68 (m, 1 H), 7.52−7.48 (m, 1 H), 7.36−7.15 (m, 10 H), 7.03−6.87 (m, 5 H), 6.39−6.35 (m, 2 H), 6.15 (dd, J = 11.7 Hz, J = 8.0 Hz, 1 H), 6.06−6.04 (m, 1 H), 3.82−3.79 (m, 3 H), 3.67 (s, 5 H), 3.40−3.39 (m, 1 H). ^{13}C{^{1}H} NMR (75 MHz, $CDCl_3$): δ 151.2−150.7 (m), 147.9 (dd, J = 26.8 Hz, J = 8.8 Hz), 147.0−146.5 (m), 138.0 (d, J = 11.7 Hz), 137.2 (d, J = 12.2 Hz), 135.9−127.8 (m), 126.3 (d, J = 1.7 Hz), 121.9 (d, J = 26.7 Hz), 121.0 (dd, J = 21.6 Hz, J = 1.7 Hz), 110.9 (d, J = 7.1 Hz), 110.2 (d, J = 5.9 Hz), 90.8 (d, J = 19.9 Hz), 69.0 (d, J = 10.0 Hz), 68.6, 67.9 (d, J = 6.5 Hz), 67.3, 66.1, 40.8 (dd, J = 30.9 Hz, J = 4.7 Hz). ^{31}P{^{1}H} NMR (81 MHz, $CDCl_3$): δ −17.6 (d, J = 1.5 Hz), −47.8 (d, J = 1.5 Hz). MS (EI): *m*/*z* 624 (M^+, 11), 459 (100), 393 (5), 337 (11), 183 (4). HR-MS: *m*/*z* $[M]^+$ calcd 624.1070 for $C_{37}H_{30}FeO_2P_2$, found 624.1053.

(*R*)-[(Diphenylphosphanyl)(2-(di-2-furylphosphanyl)phenyl)-methyl]ferrocene ((*R*)-1d). According to general procedure 2 (*R*)-**6b** (244 mg, 0.52 mmol) was reacted with diphenylphosphane (0.11 mL, 0.62 mmol, 1.2 equiv) in acetic acid (3 mL) at 65 °C for 2 h. The crude product was purified by chromatography with pentane/DEE (30/1) as the eluent to give the product as a yellow-brown solid (240 mg, 74% yield, 97% ee). Similarly, a racemic sample of **1d** was obtained as a yellow solid. Mp: 134 °C. $[\alpha]_D^{20} = -102.8°$ (*c* 0.80, $CHCl_3$). ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.75−7.70 (m, 1 H), 7.57−7.51 (m, 4 H), 7.43−7.25 (m, 5 H), 7.11−6.85 (m, 6 H), 6.68−6.66 (m, 1 H), 6.37−6.29 (m, 2 H), 5.65 (dd, J = 11.3 Hz, J = 6.5 Hz), 4.00−3.99 (m, 1 H), 3.91−3.89 (m, 1 H), 3.79−3.78 (m, 2 H), 3.55 (s, 5 H). ^{13}C{^{1}H} NMR (75 MHz, $CDCl_3$): δ 150.5 (dd, J = 30.0 Hz, 8.8 Hz), 148.4 (dd, J = 28.0 Hz, J = 9.9 Hz), 147.4 (d, J = 22.2 Hz, J = 2.3 Hz), 136.9 (dd, J = 15.5 Hz, J = 5.3 Hz), 134.6−110.7 (m), 92.0 (d, J = 19.8 Hz), 70.0 (d, J = 5.3 Hz), 68.4, 67.7 (d, J = 9.0 Hz), 67.3, 65.8, 41.4 (dd, J = 29.2 Hz, J = 14.9 Hz). ^{31}P{^{1}H} NMR (81 MHz, $CDCl_3$): δ 8.9 (d, J = 7.3 Hz), −61.5 (d, J = 7.3 Hz). MS (EI): *m*/*z* 625 (M + 1, 7), 624 (M^+, 16), 438 (199), 370 (50), 221 (17), 186 (59), 108 (74), 77 (3). HR-MS: *m*/*z* $[M]^+$ calcd 624.1070 for $C_{37}H_{30}FeO_2P_2$, found 624.1029. HPLC (AD, 2% *i*-PrOH, 0.6 mL/min, 254 nm): t_r/min = 13.0 (*S*), 16.2 (*R*).

(*R*)-[(Dicyclohexylphosphanyl)(2-(di-2-furylphosphanyl)phenyl)-methyl]ferrocene ((*R*)-1e). According to general procedure 2 (*R*)-**6b** (200 mg, 0.43 mmol) was reacted with dicyclohexylphosphane (0.10 mL, 0.51 mmol, 1.2 equiv) in acetic acid (3 mL) at 65 °C for 15 min. The crude product was purified by chromatography with pentane/DEE (20/1) as the eluent to give the product as a yellow solid (213 mg, 78% yield). A racemic sample of **1e** was obtained in an analogous manner as a yellow solid. Mp: 115−117 °C. $[\alpha]_D^{20} = -117.6°$ (*c* 0.77, $CHCl_3$). ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.75−7.71 (m, 1 H), 7.62−7.58 (m, 3 H), 7.36−7.32 (m, 1 H), 7.16−7.12 (m, 1 H), 6.82−6.78 (m, 1 H), 6.65−6.64 (m, 1 H), 6.41−6.37 (m, 2 H), 5.01 (dd, J = 11.1 Hz, J = 7.2 Hz), 4.26 (bs, 1 H), 4.06 (bs, 1 H), 4.02 (bs, 1 H), 3.92 (bs, 1 H), 3.37 (s, 5 H), 1.68−0.66 (m, 22 H). ^{13}C{^{1}H} NMR (75 MHz, $CDCl_3$): δ 151.6 (d, J = 10.5 Hz), 151.2 (d, J = 10.5 Hz), 151.0 (d, J = 5.9 Hz), 150.5 (d, J = 10.5 Hz), 147.7 (d, J = 2.3 Hz), 147.3 (d, J = 2.9 Hz), 134.3 (d, J = 2.9 Hz), 131.0 (dd, J = 2.9 Hz, J = 1.1 Hz), 130.7 (dd, J = 14.9 Hz, J = 5.3 Hz), 129.5, 126.0−125.9 (m), 121.4 (d, J = 25.1 Hz), 120.9 (d, J = 21.6 Hz), 110.9−110.8 (m), 94.3 (dd, J = 16.9 Hz, J = 1.1 Hz), 70.5 (d, J = 2.3 Hz), 68.2, 67.5, 67.5−67.3 (m), 65.1, 36.8 (d, J = 19.3 Hz), 36.4 (d, J = 18.7 Hz), 34.2 (dd, J = 18.9 Hz, J = 1.7 Hz), 34.0 (d, J = 19.2 Hz), 31.6 (dd, J = 15.4 Hz, J = 2.3 Hz), 30.5 (dd, J = 8.2 Hz, J = 2.3 Hz), 23.0 (dd, J = 22.8 Hz, J = 9.4 Hz), 28.1 (dd, J = 9.2 Hz, J = 5.3 Hz), 27.2 (d, J = 7.1 Hz), 26.9 (d, J = 11.1 Hz), 26.5, 26.2. ^{31}P{^{1}H} NMR (81 MHz, $CDCl_3$): δ 32.3 (d, J = 3.0 Hz), −63.0 (d, J = 3.0 Hz). MS (EI): *m*/*z* 638 (M + 1, 25), 637 (M^+, 58), 554 (36), 553 (100), 440 (12), 439 (42), 438 (10), 373 (15), 372 (55), 371 (41), 305 (5), 253 (7), 186 (10), 121 (3). HR-MS: *m*/*z* $[M]^+$ calcd 636.2009 for $C_{37}H_{42}FeO_2P_2$, found 636.2032.

Dichloro{(*R*)-[(diphenylphosphanyl-κ*P*)((2-(diphenylphosphanyl)-phenyl)methyl-κ*P*)]ferrocene}palladium(II) ([PdCl$_2$((*R*)-1a)]). A solution of (*R*)-**1a** (65 mg, 100 μmol) in benzene (2 mL) was added to a suspension of dichlorobis(acetonitrile)palladium(II) (26 mg, 100 μmol) in benzene (1 mL), and the resulting mixture was stirred at room temperature for 16 h. After filtration, the beige precipitate was washed with benzene and DEE and was dried in vacuo. Crystals suitable for X-ray diffraction were grown by vapor diffusion of hexane into a chloroform solution. Yield: 51 mg (62 μmol, 62%). Mp: > 230 °C dec. $[\alpha]_D^{20} = +97.2°$ (*c* 0.18, $CHCl_3$). ^{1}H NMR (400 MHz, DMSO-d_6): δ 8.42−8.30 (m, 2H), 8.08−7.92 (m, 3H), 7.80−7.70 (m, 2H), 7.70−7.64 (m, 1H), 7.63−7.24 (m, 13H), 7.09−6.99 (m, 1H), 6.87−6.77 (m, 2H), 5.64 (dd, J = 16.7 Hz, J = 7.4 Hz,

1H), 3.81 (bs, 1H), 3.71 (bs, 1H), 6.68 (s, 5H), 3.56 (s, 1H), 3.19 (s, 1H). $^{13}C\{^1H\}$ NMR (100.6 MHz, DMSO-d_6): δ 144.7 (d, J = 14.3 Hz), 135.9 (d, J = 11.7 Hz), 135.8, 135.3 (d, J = 10.1 Hz), 134.8 (d, J = 10.1 Hz), 134.3, 133.4 (d, J = 62.7 Hz), 132.3 (d, J = 10.5 Hz), 132.1, 131.8, 131.1, 130.4, 129.4 (d, J = 55.8 Hz), 128.7−127.9 (m), 127.2 (d, J = 11.4 Hz), 127.1 (d, J = 49.2 Hz), 126.1 (d, J = 57.8 Hz), 121.8 (d, J = 56.4 Hz), 86.0 (d, J = 9.2 Hz), 70.2, 69.3 (d, J = 4.9 Hz), 68.7, 67.1, 66.9, 39.9 (d, J = 21.2 Hz). ^{31}P NMR (162 MHz, DMSO-d_6): δ 42.9 (d, J = 18.4 Hz), 17.7 (d, J = 18.4 Hz). ESI-MS: m/z 785.0 $[M - Cl^-]^+$.

Typical Catalysis Reaction. In a dried 50 mL Schlenk flask were dissolved under Ar [Rh(NBD)]BF_4 (3.7 mg, 1 mol %) and the appropriate diphosphane ligand **1a**−**e** (1 mol %) in toluene/methanol (6 mL, 5:1). After the rhodium complex had completely dissolved, a solution of substrate (1 mmol) in methanol (4 mL) was added. Subsequently, the argon atmosphere was replaced by hydrogen and the reaction mixture was stirred at room temperature for 3−20 h (see Table 1). The solvents were removed under reduced pressure, and the residue was purified by chromatography on silica with DEE as the eluent. After the solvent was removed on a rotary evaporator, the enantiomeric excess was determined by GC (Chiralsil-*L*-Val) or HPLC (Chiralcel OD).

X-ray Structure Determination for Compounds (*R*)-4 and [$PdCl_2$(*R*)-1a]. X-ray data were collected on a Bruker Smart APEX CCD area detector diffractometer using graphite-monochromated Mo Kα radiation (λ = 0.710 73 Å) and a combination of φ- and ω-scan frames. Corrections for absorption and $\lambda/2$ effects were applied.[11] The structures were solved with the program SHELXS97 and direct methods; refinement on F^2 was carried out with the program SHELXL97.[12] Non-hydrogen atoms were refined anisotropically. Most H atoms were placed in calculated positions and thereafter treated as riding. The absolute structures could be unambiguously determined by anomalous dispersion effects and the Flack absolute structure parameter (FASP). Important crystallographic data are as follows.

(*R*)-**4**: $C_{17}H_{15}BrFeO$, M_r = 371.05, orange cube from dichloromethane/hexane, 0.35×0.31×0.28 mm, orthorhombic, space group $P2_12_12_1$, a = 8.0597(4) Å, b = 11.2942(5) Å, c = 15.5563(7) Å, V = 1416.06(11) Å^3, Z = 4, μ = 3.878 mm^{-1}, d_x = 1.740 g cm^{-3}, T = 100 K, 21 084 reflections collected (θ_{max} = 30.0°) and merged to 4112 independent data (R_{int} = 0.0207), final R indices (all data) R1 = 0.0226 and wR2 = 0.0566, 185 parameters, FASP = −0.011(6).

[$PdCl_2$(*R*)-**1a**] as the chloroform solvate [$PdCl_2$(*R*)-**1a**]·3$CHCl_3$: $C_{44}H_{37}Cl_{11}FeP_2Pd$; M_r = 1179.88, orange prism from chloroform, 0.45 × 0.19 × 0.11 mm, monoclinic, space group $P2_1$, a = 11.0239(2) Å, b = 18.0739(3) Å, c = 11.9896(2) Å, β = 99.709(1)°, V = 2354.65(7) Å^3, Z = 2, μ = 1.415 mm^{-1}, d_x = 1.664 g cm^{-3}, T = 100 K, 34 674 reflections collected (θ_{max} = 30.0°) and merged to 13 485 independent data (R_{int} = 0.0239), final R indices (all data) R1 = 0.0408 and wR2 = 0.0988, 532 parameters, FASP = 0.001(15).

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Supporting Information Available: CIF files giving complete crystallographic data and technical details for compounds (*R*)-**4** and [$PdCl_2$(*R*)-**1a**]·3$CHCl_3$. This material is available free of charge via the Internet at http://pubs.acs.org.

(11) Bruker programs: *APEX2, version 2009.9-0*; *SAINT, version 7.68A*; *SADABS, version 2008/1*; *SHELXTL, version 2008/4*; Bruker AXS Inc., Madison, WI, 2009.

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