A Novel Class of Ferrocenyl-Aryl-Based Diphosphine Ligands for Rh- and Ru-Catalysed Enantioselective Hydrogenation

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Received: July 27, 2002; Accepted: October 30, 2002

Abstract: A series of diphosphines of the novel Walphos ligand family all based on a phenylferrocenylethyl backbone were synthesised in a four-step sequence. In the rhodium- or ruthenium-catalysed asymmetric hydrogenation of olefins and ketones enantioselectivities of up to 95% and 97%, respectively, were obtained. A 2-isopropylcinnamic acid derivative of industrial interest was hydrogenated in 95% ee and with turnover numbers of >5000.

Keywords: alkene reduction; asymmetric catalysis; asymmetric hydrogenation; ketone reduction; P-ligands; rhodium; ruthenium

Over a period of more than three decades homogenous enantioselective hydrogenation has been investigated extensively by numerous researchers in academia and industry, and is now being considered as a mature methodology for the production of enantiopure, bioactive ingredients and fine chemicals on an industrial scale.[1] The most efficient catalysts for the asymmetric hydrogenation of olefins, ketones or imines[2] are rhodium, ruthenium and iridium complexes of chiral diphosphine ligands. However, even though innumerable chiral diphosphines have been designed and investigated in the past, only a few out of more than thousands have been found suitable for industrial processes. Representative examples are biaryl-, phospholane- and ferrocenyl-based ligands like binap, duphos or josiphos type ferrocenes.[3]

In our search for novel classes of diphosphines, we focused on the design of ligands that fulfil all relevant prerequisites particularly with regard to industrial applications: shortness and modularity of ligand synthesis that should allow an efficient fine tuning of catalysts' properties. In addition, such ligands should be readily accessible from enantiopure key intermediates. In this context, we have examined the potential of a new family with a novel phenylferrocenylethyl backbone that we named Walphos (**1**; Figure 1). The synthesis concept for this ligand family is straightforward: (i) the enantiomerically pure ligand framework – an *ortho*-bromophenylferrocenylethylamine (**3**) – is constructed from Ugi's amine[4] and (ii) the final functional groups are implemented stepwise.[5] (Scheme 1) In this preliminary contribution, we report the synthesis of six representatives of the Walphos family with varying phosphino substituents R^1 and R^2, together with first applications in the enantioselective hydrogenation.

Starting from amine **2**, six derivatives with electron-rich and electron-withdrawing phosphino substituents R^1 and R^2 were prepared in a four-step sequence. In a Negishi coupling reaction[6] of (R_c)-*N*,*N*-dimethyl-1-ferrocenylethylamine, (R_c)-**2**, with 2-bromoiodobenzene the enantiomerically pure key intermediate (R_c,R_p)-**3** was built up. A subsequent lithiation of this bromide followed by trapping with the appropriate electrophile – either chlorodiphenylphosphine or chlorobis(3,5-dimethyl-4-methoxyphenyl)phosphine – resulted in the formation of the corresponding aminophosphines. In order to prevent a ring closure reaction in the next step, the aminophosphines had to be protected by oxidation with H_2O_2 to afford the corresponding phosphine oxides (R_c,R_p)-**4a** and (R_c,R_p)-**4f**, respectively.

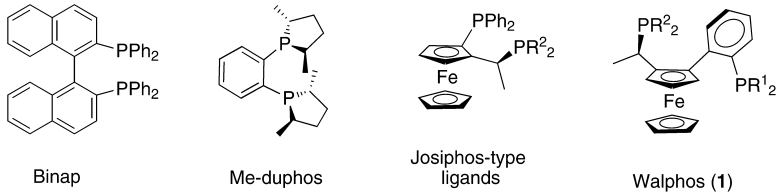

Figure 1. Examples of diphosphine ligands used in industrial enantioselective hydrogenation processes.

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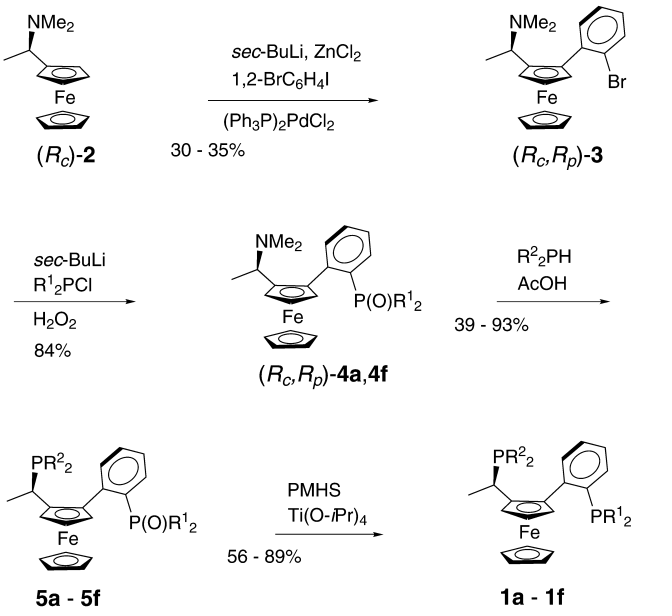


a	R^1 = Ph	R^2 = Cy
b	R^1 = Ph	R^2 = *tert*-Bu
c	R^1 = Ph	R^2 = 3,5-$(CH_3)_2$-4-$(CH_3O)C_6H_2$
d	R^1 = Ph	R^2 = Ph
e	R^1 = Ph	R^2 = 3,5-$(CF_3)_2C_6H_3$
f	R^1 = 3,5-$(CH_3)_2$-4-$(CH_3O)C_6H_2$	R^2 = 3,5-$(CF_3)_2C_6H_3$

Scheme 1. Synthesis of ligands **1a – 1f**.

Treatment of (R_c,R_p)-**4a** with either a dialkyl- or diarylphosphine (R^2_2PH) in acetic acid[7] led to derivatives **5a – 5e** [R^2 = Cy: **5a**; *t*-Bu: **5b**; 3,5-$(CH_3)_2$-4-$CH_3OC_6H_2$: **5c**; Ph: **5d**; 3,5-$(CF_3)_2C_6H_3$: **5e**] while reaction of (R_c,R_p)-**4f** with [3,5-$(CF_3)_2C_6H_3]_2PH$ gave **5f**. It is interesting to note that **5a – 5c** were obtained in diastereomerically pure form with (R_c,R_p) configurations, indicating clean retention of configuration in the nucleophilic substitution step. However, in the case of **5d – 5f** the respective (S_c,R_p)-diastereomer was formed as a by-product [ratio of (R_c,R_p)/(S_c,R_p) diastereomers; **5d**: 10/1; **5e**: 6/1; **5f**: 6/1]. In this particular case the observed diastereoselectivity of the nucleophilic substitution step seems to depend strongly on the nucleophilicity of the phosphine, since only the electron-rich phosphines gave products with full retention of configuration (**5a – 5c**). Reduction of **5a – 5f** (in the case of **5d – 5f** the mixtures of diastereomer were used) with polymethylhydrosiloxane (PMHS)/titanium isopropoxide[8] or trichlorosilane/triethylamine[9] gave the desired Walphos ligands **1a – 1f**. Separation of major diastereomers was achieved by flash chromatography.

All ligands **1a – 1f** of (R_c,R_p) configuration were screened in catalytic hydrogenation of olefins and ketones (for substrates see Figure 2). All catalysts were formed *in situ* with use of an appropriate Rh or Ru source (see footnotes to Tables). In each hydrogenation reaction, conversion was quantitative or nearly quantitative (Tables 1 and 2). The diphosphines **1c – 1e** proved to be particularly valuable ligands in rhodium-catalysed hydrogenations of olefins (Table 1) while **1e** and **1f** gave excellent results in ruthenium-catalysed hydrogenations of ketones (Table 2).

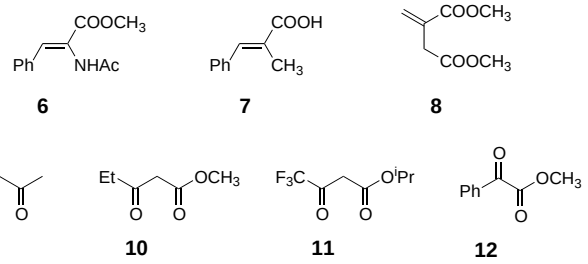


Figure 2. Olefins and ketones used as substrates in catalytic hydrogenations.

The hydrogenation of α-acetamidocinnamic acid (**6**) and dimethyl itaconate (**8**) afforded *N*-acetylphenylalanine methyl ester and dimethyl 2-methylsuccinate with 95% and 91% enantiomeric purity, respectively, while 2-methylcinnamic acid (**7**) gave 2-methyl-3-phenylpropionic acid of 82% ee. (Table 1, entries 3, 12 and 14). For both substrates, **6** and **8**, catalysts prepared with ligands **1c – 1e** with two diarylphosphino substituents (R^1 = R^2 = aryl) yielded hydrogenation products of higher enantioselectivity than **1a** and **1b** with one diaryl- and one dialkylphosphino unit (R^1 = Ph, R^2 = alkyl). However, it is interesting to note that for **6** as the substrate ligand **1c** with an electron-donating phosphino group [R^2 = 3,5-$(CH_3)_2$-4-$CH_3OC_6H_2$] gave the best result, while in the case of olefin **7** ligand **1e** with an electron-withdrawing phosphino group [R^2 = 3,5-$(CF_3)_2C_6H_3$] performed best. As shown with the catalyst $[(NBD)_2Rh]BF_4$/**1d** in the hydrogenation of **6**, both pressure and temperature significantly influence the enantioselectivity. Increasing the pressure from 1 to 10 bar results in lowering of the enantiomeric purity of the *N*-acetylphenylalanine methyl ester from 87% to 82% (Table 1, entries 4 and 5). At lower temperatures, i.e., at 5 °C, a higher enantiomeric excess was obtained than at 25 °C: 90% compared to 87% (Table 1, entries 4 and 6).

In the hydrogenation of ketones, the test substrates were a 1,3-diketone (acetylacetone, **9**, Figure 2), β-keto esters (**10**, **11**) and an α-keto ester (**12**). Typically, *turnover numbers* of 1,000 were obtained smoothly, and the average *turnover frequency* (*tof*) of approximately 200 h^{-1} (entry 2) as measured for example in the Ru/**1f**-catalysed hydrogenation of **9** is sufficiently high for evaluation of synthetic applications. In ruthenium-mediated hydrogenations, the ligands **1e** and **1f** with either one electron-donating diarylphosphino or one diphenylphosphino group attached to the phenyl part of the scaffold and one electron-withdrawing phosphino

Table 1. Rhodium-catalysed hydrogenation of olefins.

Entry	Substrate	Ligand	p(H_2) [bar]	T [°C]	Time [h]	Conv. [%]	ee [%]	Config.
1[d]	**6**[a, b]	**1a**	1	25	18	> 97	25	*(R)*
2	**6**	**1b**	1	25	66	> 99	8	*(R)*
3	**6**	**1c**	1	25	20.5	> 99	**95**	*(R)*
4[d]	**6**	**1d**	1	25	17.5	> 98	87	*(R)*
5	**6**	**1d**	10	25	18	> 99	82	*(R)*
6	**6**	**1d**	1	5	19	> 99	90	*(R)*
7	**6**	**1e**	1	25	20.5	> 99	60	*(R)*
8	**7**[a, c]	**1a**	5	25	21	> 99	51	*(R)*
9	**7**	**1b**	5	25	18	> 99	31	*(R)*
10	**7**	**1c**	5	25	22	> 98	68	*(R)*
11	**7**	**1d**	5	25	20.5	> 98	66	*(R)*
12	**7**	**1e**	5	25	20	> 99	**82**	*(R)*
13	**8**[a, e]	**1d**	1	0	16	> 99	90	*(R)*
14	**8**	**1e**	1	25	21	> 99	**91**	*(R)*

[a] Catalyst precursor: $[(NBD)_2Rh]BF_4$; S/C = 200; solvent: methanol (10 mL); Ligand/Rh = 1.1.
[b] ee determination by GC on Chirasil-*L*-Val, (He carrier, 135 °C, isothermic).
[c] ee determination as methyl ester by HPLC on Chiralcel OB, (Daicel; eluent: hexane/2-propanol = 97/3, flow: 0.1 mL/min).
[d] S/C = 187.
[e] ee determination by GC on Lipodex-E, (He carrier, 100 °C, isothermic).

Table 2. Ruthenium-catalysed hydrogenation of ketones.

Entry	Substrate	Ligand	p(H_2) [bar]	T [°C]	Time [h]	Conv. [%]	ee [%]	Config.
1[a, b]	**9**	**1e**	100	80	17	> 99	**97**	*(2R,4R)*[h]
2[a, b]	**9**	**1f**	20	80	16[g]	> 99	96	*(2R,4R)*[h]
3[a, c]	**10**	**1a**	100	80	19	> 99	50	*(S)*
4[a, c]	**10**	**1e**	100	80	16.5	> 99	91	*(S)*
5[a, c]	**10**	**1f**	20	80	16,5	> 99	94	*(S)*
6[a, c]	**10**	**1f**	20	60	16.5	> 99	94	*(S)*
7[a, c]	**10**	**1f**	100	80	17.5	> 99	90	*(S)*
8[a, c]	**10**	**1f**	100	60	17	> 99	91	*(S)*
9[a, c]	**10**	**1f**	5	80	16	> 99	**95**	*(S)*
10[a, c,d]	**11**	**1e**	20	77	16	> 99	77	*(S)*
11[a, c,d]	**11**	**1f**	20	80	16	> 99	60	*(S)*
12[a, f]	**12**	**1f**	20	80	16	> 90	22	*(R)*

[a] Catalyst precursor: $[RuI_2(p\text{-cymene})]_2$; S/C = 1000; Ligand/Ru = 1.1; solvent: methanol (10 mL); additives: 1 N HCl (120 μL).
[b] ee determination as bis(trifluoroacetate) by GC on Lipodex-E, (He carrier, 80 °C, isothermic).
[c] ee determination as trifluoroacetate by GC on Lipodex-E, (He carrier, 80 °C, isothermic).
[d] Solvent: 2-propanol (10 mL).
[e] ee determination by GC on Chirasil-*L*-Val, (45 °C, isothermic).
[f] ee determination by HPLC on Chiralcel OJ (Daicel; eluent: hexane/2-propanol = 9/1, flow: 0.1 mL/min).
[g] Time for complete hydrogen uptake: 5 h;
[h] *rac.*:*meso* > 99:1.

substituent at the stereogenic C atom, performed best. For substrates **9** and **10**, products with enantioselectivities of 97% and 95% were obtained (Table 2, entries 1, 9). In the case of **10**, both the temperature and the pressure dependence was found to be rather small (entries 5 – 9). Only when the hydrogen pressure was raised to 100 bar did the enantioselectivity drop slightly (90%, entry 7). In contrast, the hydrogenation of α-keto ester **12** by means of Ru/**1f** afforded methyl mandelate only with 22% enantiomeric purity.

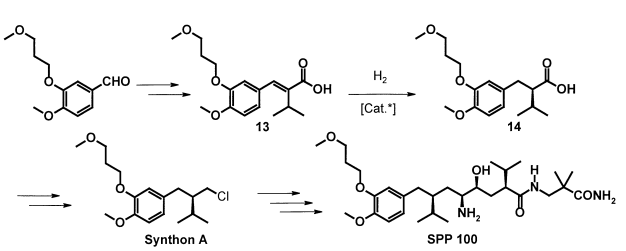
Overall, these results obtained with the Walphos ligands **1e** and **1f** in the hydrogenation of β-keto esters and the 1,3-diketone are relatively remarkable. Only a few Ru catalysts with ligands other than atropisomeric diphosphines have been reported to hydrogenated such functionalised ketones efficiently with high enantioselection, i.e., bis(phospholanes),[10] taniaphos,[11] or josiphos.[7] Hence, the application of Walphos ligands could be a valuable alternative to the atropisomeric diaryldiphosphines.

In order to evaluate the synthetic potential of the Walphos family and encouraged by the very promising screening results, particularly with ligands **1c**, **1e**, and **1f**, the enantioselective hydrogenation of the substituted acyclic acid **13** was investigated. Synthon A is an intermediate for the synthesis of the renin inhibitor SPP100, which is currently being developed.[12] The key step for the preparation of the enantiopure Synthon A is the enantioselective hydrogenation of **13**. The application of 1 mol % of an Rh catalyst generated *in situ* from $[(NBD)_2Rh]BF_4$ and ligand **1e** afforded at 50 bar hydrogen and ambient temperature the saturated acid **14** with 95% ee. All of the other diphosphines available on technical scale afforded **14** with significantly lower enantiomeric purity. Among the various other catalysts tested at 20–60 bar hydrogen and 40–50 °C, the cationic Rh catalyst with (*S,S*)-Me-duphos provided **14** only with 15% ee. Rh/(*R*)-MeO-biphep hydrogenated **13** with 35% ee (*S*), Rh/(*R*)-(*S*)-PPF-*t*-Bu_2[7] with 49% ee (*S*), Rh/**1d** with 79% (*S*), and Achiwa's (2*S*,4*S*)-bcpm yielded **14** with fairly high 80% ee (*S*).

We rationalised that this remarkably high enantioselectivity of the Rh/**1e** catalyst compared with the hydrogenation of model substrate **7** is probably due to a large extent to the bulkier substituent at the C-2 position of the cinnamic acid derivative **13**. However, we anticipate the electronic effects of the two alkoxy substituents of the aryl moiety of **13** to trigger the enantioselectivity, too.

At bench-scale under technical reaction conditions, 39 mol of **13** could be hydrogenated with an S/C = 5700 yielding intermediate **14** with 95% ee.

In conclusion, we have prepared six derivatives of a novel diphosphine family named Walphos with a phenylferrocenylethyl scaffold and tested their potential in enantioselective hydrogenation reactions. The concise and modular synthesis allows the efficient incorporation of two different phosphino groups in two subsequent steps. The results obtained in the initial screening showed the versatility of the Walphos ligand family. More results documenting our current investigations on scope and limitations of this ligand family will be published in due course.



Scheme 2. Synthesis of Synthon A, a key intermediate in the preparation of the renin inhibitor SPP100.

Experimental Section

General

The synthesis of all ligands **1a**–**1f** starts from commercially available enantiopure (*R*)-**2** and follows the reaction sequence given in Scheme 1. Typical reaction procedures are given for ligand **1d**. All other ligands were prepared analogously.[14]

($R_\sigma R_p$)-1-[1-(Diphenylphosphino)ethyl]-2-(2-diphenylphosphinylphenyl)-ferrocene (5d)

To a degassed solution of 1.2 g (2.25 mmol) **4a** in 15 mL acetic acid were added 0.72 mL (4 mmol) of diphenylphosphine and the reaction mixture was stirred at 100 °C for 18 hours. After a saturated aqueous solution of $NaHCO_3$ had been added the organic layer was separated and the aqueous layer was extracted twice with 30 mL of CH_2Cl_2. The combined organic layers were dried over $MgSO_4$ and after removal of the solvent the residue was purified by chromatography on alumina. Petrol ether eluted non-polar impurities and subsequently CH_2Cl_2 eluted the product as a mixture of diastereomers. Yield: 1.330 g (1.97 mmol, 89.8%). According to ^{31}P NMR the ratio of the ($R_\sigma R_p$) and ($S_\sigma R_p$) diastereomers was found to be 10:1. ^1H and ^{13}C NMR data are given for the major isomer only. ^1H NMR: δ = 1.40 (dd, $J_1 = J_2 = 7.0$ Hz, 3H), 3.67 (m, 1H, Cp), 3.73 (q, J = 7.0 Hz, 1H), 3.80 (t, J = 2.5 Hz, 1H, Cp), 4.03 (s, 5H, Cp), 5.15 (m, 1H, Cp), 7.13–7.31 (m, 13H, Ph), 7.37–7.48 (m, 4H, Ph), 7.49–7.59 (m, 4H, Ph), 7.65–7.70 (m, 2H, Ph), 8.28–8.31 (m, 1H, Ph). ^{13}C NMR: δ = 17.53 (CH_3), 28.06 (d, J = 19.9 Hz, CH), 65.38 (Cp), 67.82 (d, J = 4.6 Hz, Cp), 70.13 (5 Cp), 70.47 (d, J = 2.3 Hz, Cp), 86.56 (q-Cp), 93.14 (d, J = 21.6 Hz, q-Cp), 125.91 (d, J = 13.0 Hz, Ph), 127.64 (d, J = 6.1 Hz, Ph), 127.67 (Ph), 128.15–128.51 (3 Ph), 130.62 (d, J = 3.1 Hz, Ph), 130.81 (d, J = 2.4 Hz, Ph), 131.09 (d, J = 3.1 Hz, Ph), 131.27 (d, J = 3.8 Hz, Ph), 131.37 (d, J = 3.8 Hz, Ph), 132.02 (d, J = 8.4 Hz, Ph), 132.21 (d, J = 16.8 Hz, Ph), 132.70 (q-Ph), 133.75 (q-Ph), 134.54 (d, J = 9.9 Hz, Ph), 134.79 (d, J = 19.9 Hz, Ph), 134.78 (q-Ph), 135.17 (d, J = 12.2 Hz, Ph), 136.17 (d, J = 22.0 Hz, q-Ph), 138.44 (d, J = 19.2 Hz, q-Ph), 143.31 (d, J = 7.2 Hz, q-Ph). ^{31}P NMR: major isomer: δ = 4.25, 31.38; minor isomer: δ = 3.41, 29.91. MS: *m/e* (rel %) = 674.0 (6.7, M^+), 609.9 (11.8), 608.8 (24.6), 489.9 (11.5), 488.8 (31.0), 423.9 (40.0), 422.9 (100.0), 182.9 (24.4), 165.0 (13.6), 120.9 (11.6). HRMS: calcd. for $C_{42}H_{36}FeOP_2$: 674.1853; found: 674.1612.

($R_\sigma R_p$)- and ($S_\sigma R_p$)-1-[(1-Diphenylphosphino)ethyl]-2-(2-diphenylphosphinophenyl)-ferrocene [($R_\sigma R_p$)-1d and ($S_\sigma R_p$)-1d]

To a solution of 1.2 g (1.78 mmol) phosphine oxide **5d** in 20 mL of THF were added 7 mL of polymethylhydrosiloxane and 3.8 mL of Ti(O-*i*-Pr)$_4$. The solution was degassed and subsequently refluxed for 18 hours. After addition of 15 mL hexane the reaction mixture was refluxed for additional two hours. The reaction mixture was poured into 25 mL of water and the organic layer was separated. The aqueous layer was extracted with hexane (3 × 20 mL) and the combined organic layers were washed with water (2 × 20 mL). After drying over $MgSO_4$ and evaporation of the solvent the residue was

chromatographed on alumina (petrol ether/chloroform = 8/2) to afford 971 mg (1.48 mmol, 83%) of **1d** as a mixture of two diastereomers, which were separated in a second chromatography on silica (eluent: petrol ether/methylene chloride = 7/3).

(R_c,R_p)-1c: mp 73–77 °C; ^{1}H NMR: δ = 1.28 (dd, $J_1 = J_2$ = 7.2 Hz, 3H), 3.40 (q, J = 7.2 Hz, 1H), 3.62 (m, 1H, Cp), 3.84 (m, 1H, Cp), 3.93 (m, 1H, Cp), 4.05 (s, 5H, Cp), 6.90–6.94 (m, 1H, Ph), 7.06–7.23 (m, 14H, Ph), 7.25–7.36 (m, 8H, Ph), 8.03–8.06 (m, 1H, Ph). ^{13}C NMR: δ = 16.48 (CH_3), 28.71 (d, J = 19.9 Hz, CH), 65.07 (Cp), 66.92 (d, J = 5.4 Hz, Cp), 69.43 (5 Cp), 70.96 (d, J = 10.7 Hz, Cp), 89.80 (q-Cp), 92.26 (d, J = 18.2 Hz, q-Cp), 126.94 (Ph), 127.07 (Ph), 127.58 (d, J = 7.6 Hz, Ph), 127.72 (Ph), 128.01–128.09 (3 Ph), 128.31 (Ph), 128.39 (d, J = 6.9 Hz, Ph), 128.75 (Ph), 131.70 (dd, J_1 = 1.5 Hz, J_2 = 15.3 Hz, Ph), 132.81 (d, J = 5.4 Hz, Ph), 133.47 (dd, J_1 = 3.1 Hz, J_2 = 18.4 Hz, Ph), 134.01 (d, J = 19.9 Hz, Ph), 134.74 (d, J = 2.3 Hz, Ph), 135.50 (d, J = 22.2 Hz, q-Ph), 135.64 (dd, J_1 = 3.1 Hz, J_2 = 20.7 Hz, Ph), 138.47 (dd, J_1 = 1.5 Hz, J_2 = 13.9 Hz, q-Ph), 138.66 (d, J = 6.8 Hz, q-Ph), 138.83 (q-Ph), 139.59 (d, J = 15.1 Hz, q-Ph), 143.26 (d, J = 30.5 Hz, q-Ph). ^{31}P NMR: δ = –13.74 (d, J = 16.4 Hz), 3.77 (d, J = 16.4 Hz); MS: *m/e* (rel %) = 657.8 (49.5, M^+), 472.7 (100), 406.7 (22.1), 350.8 (12.2), 182.9 (9.5), 97.0 (21.6); HRMS: calcd. for $C_{42}H_{36}FeP_2$): 658.1642; found: 658.1640; anal. calcd. for $C_{42}H_{36}FeP_2$: C 76.60, H 5.51, P 9.41%; found: C 76.39, H 5.76, P 9.17%. $[\alpha]^{20}$ (nm): +9.4° (589), 0° (578), –65.2° (546) (*c* 0.5, $CHCl_3$); CD: Δε (nm) = 28.88 (236), 28.71 (242), –2.70 (304), 4.07 (349), –1.45 (467) (*c* 1 × 10^{-3}, CH_2Cl_2).

(S_c,R_p)-1c: mp 157–170 °C; ^{1}H NMR: δ = 0.79 (dd, J_1 = 7.0 Hz, J_2 = 9.0 Hz, 3H), 3.28 (dq, J_1 = 4.0 Hz, J_2 = 7.0 Hz, 1H), 3.76–3.78 (m, 1H, Cp), 3.93 (s, 5H, Cp), 4.03 (t, J = 2.5 Hz, 1H, Cp), 4.11 (m, 1H, Cp), 6.91–6.94 (m, 1H, Ph), 6.96–7.00 (m, 2H, Ph), 7.08–7.13 (m, 3H, Ph), 7.17–7.34 (m, 12H, Ph), 7.36–7.41 (m, 1H, Ph), 7.45–7.50 (m, 2H, Ph), 7.53–7.57 (m, 2H, Ph), 7.95–7.98 (m, 1H, Ph). ^{13}C NMR: δ = 21.41 (dd, J_1 = 3.8 Hz, J_2 = 6.9 Hz, CH_3), 29.07 (d, J = 14.5 Hz, CH), 65.73 (Cp), 67.28 (d, J = 9.2 Hz, Cp), 69.82 (5 Cp), 70.64 (dd, J_1 = 2.3 Hz, J_2 = 9.9 Hz, Cp), 89.87 (dd, J_1 = 6.8 Hz, J_2 = 11.4 Hz, q-Cp), 93.83 (d, J = 18.3 Hz, q-Cp), 127.11 (Ph), 128.05 (d, J = 1.5 Hz, Ph), 128.09 (d, J = 7.6 Hz, Ph), 128.14 (d, J = 1.5 Hz, Ph), 128.21 (Ph), 128.33–128.43 (4 Ph), 128.83 (Ph), 133.25 (d, J = 17.6 Hz, Ph), 133.49 (d, J = 19.9 Hz, Ph), 133.80 (d, J = 19.9 Hz, Ph), 133.81 (d, J = 5.4 Hz, Ph), 134.12 (d, J = 1.4 Hz, Ph), 135.03 (d, J = 21.4 Hz, Ph), 137.66 (d, J = 15.4 Hz, q-Ph), 137.81 (d, J = 9.9 Hz, q-Ph), 138.54 (d, J = 12.8 Hz, q-Ph), 138.76 (d, J = 13.5 Hz, q-Ph), 138.90 (d, J = 14.7 Hz, q-Ph), 143.01 (d, J = 30.5 Hz, q-Ph); ^{31}P NMR: δ = –14.40 (d, J = 5.9 Hz), –1.82 (d, J = 5.9 Hz); MS: *m/e* (rel %) = 658.4 (19.3, M^+), 474.1 (40.3), 473.0 (100), 407.1 (25.3), 337.1 (11.1), 183.0 (11.7); HRMS: calcd. for $C_{42}H_{36}FeP_2$: 658.1642; found: 658.1648; $[\alpha]^{20}$ (nm): +88.6° (589), +81.1° (578), +25.7° (546) (*c* 0.49, $CHCl_3$).

Standard Procedure for Hydrogenation Reactions

The substrate (2.53 mmol) and the catalyst (formed *in situ*, for details see Tables 1 and 2) were dissolved separately in 5 mL of the solvent under argon (total volume: 10 mL). The catalyst solution was stirred for 15 min. Both the catalyst and the substrate solution were transferred *via* a steel capillary into a 180 mL thermostatted glass reactor or a 50 mL stainless steel autoclave. The inert gas was then replaced by hydrogen (three cycles) and the pressure was set. After completion of the reaction (total reaction times 16–66 h), the conversion was determined by gas chromatography and the product was recovered quantitatively after filtration of the reaction solution through a plug of silica to remove the catalyst. The enantiomeric purity of the product was determined either by gas chromatography or by HPLC (see footnotes in Tables 1 and 2).

Acknowledgements

This work was kindly supported by Novartis Services AG (T.S., W.W.). We acknowledge the skilful technical assistance of Andrea Holderer, Robert Häusel and Bernd Geiser.

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