Available online at www.sciencedirect.com
SCIENCE DIRECT®
Tetrahedron: Asymmetry 16 (2005) 3385–3393
Tetrahedron: Asymmetry

Synthesis of JOSIPHOS-type ligands via a diastereoselective three-component reaction and their application in asymmetric rhodium-catalyzed hydroborations

Shuji Yasuike, Christiane C. Kofink, Ralf J. Kloetzing, Nina Gommermann, Katja Tappe, Andrei Gavryushin and Paul Knochel*

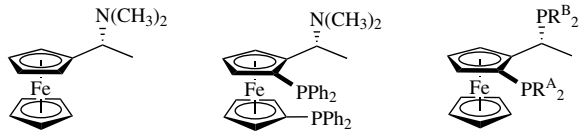
Department of Chemistry of Ludwig-Maximilians-University, Butenandtstrasse 5-13, 81377 Munich, Germany

Received 4 August 2005; accepted 30 August 2005
Available online 20 October 2005

Abstract—The recently reported diastereoselective three-component reaction for the synthesis of chiral propargylamines was used for a new stereoselective synthesis of JOSIPHOS-type ligands **2a**–**d**. The present synthesis gives the desired diphosphines in good yields without the need of resolution. Ligands **2a**–**d** were applied to the rhodium-catalyzed hydroboration of styrene.

1. Introduction

Ferrocenyl ligands occupy a special place in enantioselective transition-metal catalyzed reactions.[1,2] Due to their conformational rigidity, the facile combination of planar chirality and the presence of stereogenic centers in side chains, the versatile ferrocene framework facilitated the preparation of very efficient ligands for asymmetric synthesis. In particular, ferrocene-based diphosphines were used successfully as ligands for selective asymmetric reductions.[3] Ugi's amine[4] proved to be an excellent starting point for the synthesis of ferrocenyl ligands, as was demonstrated by Hayashi and Kumada (BPPFA).[5] In his pioneer investigations, Togni has used Ugi's amine to prepare JOSIPHOS,[6] one of the most successful ligands for asymmetric catalysis (Scheme 1).

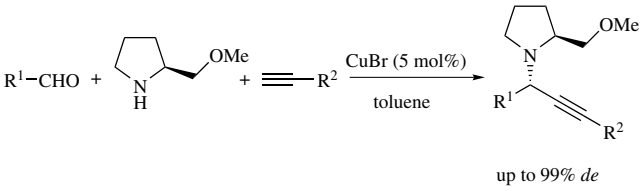


Ugi's amine | (*R*)-(*S*)-BPPFA | (*R*)-(*S*)-JOSIPHOS
1a: R^A: phenyl
R^B: cyclohexyl

Scheme 1. Important ferrocenyl ligands.

JOSIPHOS has found industrial applications in rhodium-[7] and iridium-catalyzed[8] hydrogenation reactions while new applications are continuously being developed.[9] JOSIPHOS is a very versatile ligand since the substituents R^A and R^B can be varied independently allowing the modular synthesis of broad libraries of ligands (Scheme 1).

Recently, we reported a new copper-catalyzed enantioselective three-component reaction for the synthesis of chiral progargylamines (Scheme 2).[10]



up to 99% *de*

Scheme 2. Diastereoselective three-component reaction.

Benzaldehyde ($R^1 = Ph$) reacts with phenylacetylene ($R^2 = Ph$) and (*S*)-2-(methoxymethyl)pyrrolidine to give the corresponding progargylamine in high yield and diastereoselectivity (87%, 92% de). This reaction allows the formation of a new carbon–carbon bond and a stereogenic center with excellent control of stereochemistry in a single step.

* Corresponding author. Tel.: +49 (0) 89 2180 77681; fax: +49 (0) 89 2180 77680; e-mail: paul.knochel@cup.uni-muenchen.de

0957-4166/$ - see front matter © 2005 Elsevier Ltd. All rights reserved.
doi:10.1016/j.tetasy.2005.08.051

We herein report the synthesis of JOSIPHOS derivatives using the new efficient three-component reaction, since this excellent ligand is a rewarding objective for enantioselective organic synthesis.

2. Synthesis

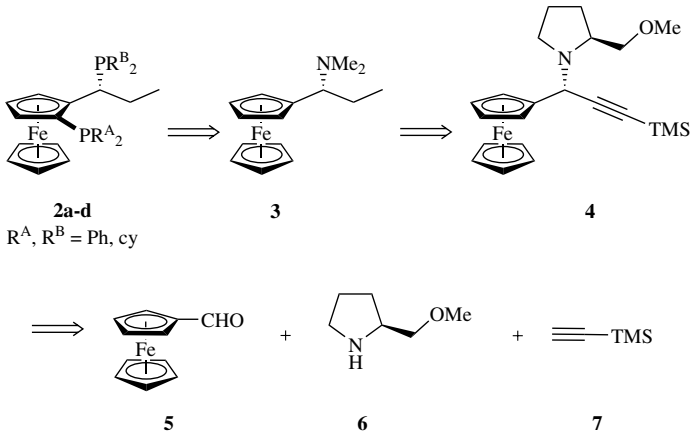
This new approach should enable us to prepare an ethyl analogue of JOSIPHOS in an efficient stereoselective approach. Compound **2a** features an alkyl group in the side chain whereas JOSIPHOS **1a** has a methyl group at this position.

The key intermediate of this synthesis is amine **3**, which allows the preparation of ligands **2a–d** using the same methods as Togni applied for the synthesis of JOSIPHOS **1a** starting from Ugi's amine.[6a,11] We planned to prepare amine **3** by reduction of the triple bond and substitution of the amine from the ferrocenyl propargylamine **4** according to the retrosynthetic analysis depicted in Scheme 3.

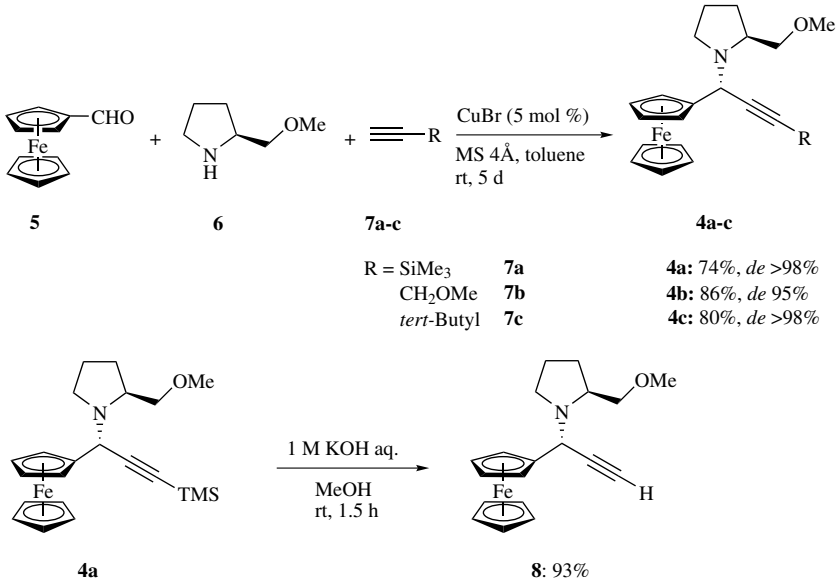
The copper-catalyzed three-component reaction of ferrocene carbaldehyde **5**, (*S*)-2-(methoxymethyl)-pyrrolidine[12] **6** and several terminal alkynes **7a–c** gave amines **4a–c** with good yields and excellent diastereoselectivity. The silyl protection group in **4a** was cleaved hydrolytically by aqueous KOH (Scheme 4).

The hydrogenation of acetylene **8** to amine **9** with Pd/C in methanol was accompanied by the reductive cleavage of the C–N bond at the α-position of the ferrocene to give propyl-ferrocene **10** as a side product. Various additives and solvents were examined in order to improve the yield of amine **9** (Scheme 5 and Table 1).

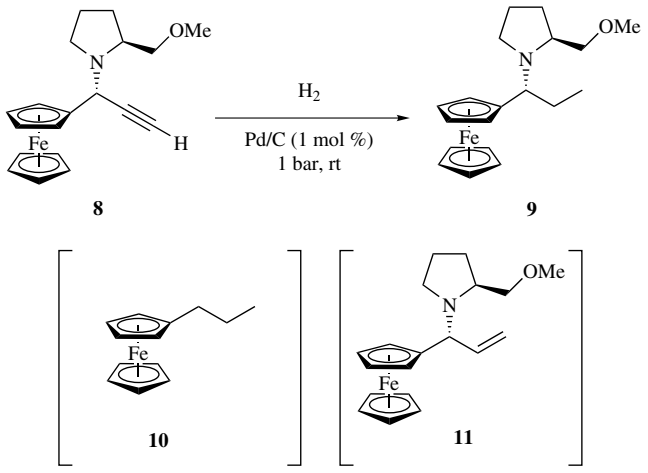
Without an additive (entry 1 of Table 1), the ratio of side product **10** and product **9** was 2:1. The addition of sodium hydroxide solution reduced the amount of side product **10**. The yield of product **9** could be improved, but the hydrogenation became less efficient and the substantial amounts of olefin **11** were isolated (entry 2). The addition of amines (entries 3 and 4) completely inhibited the reaction. Other solvents such



Scheme 3. Retrosynthetic analysis.



Scheme 4. Three-component reaction and deprotection.



Scheme 5. Hydrogenation of alkyne **8**.

Table 1. Hydrogenation of alkyne **8**[a]

	Solvent	Additive	Time (h)	Yield (%)[b]		
				9	**10**	**11**
1	MeOH	—	1.5	28	56	—
2	EtOH	2.0 M NaOH (10 mol %)	2	43	24	32
3	EtOH	Et_3N (15 mol %)	3	—	—	—
4	EtOH	Quinoline (15 mol %)	3	—	—	—
5	EtOH–toluene	2.0 M NaOH (10 mol %)	2	20	12	65
6	CH_2Cl_2	0.2 M NaOH (5 mol %)	1.5	31	26	24
7	EtOH	0.2 M NaOH (20 mol %)	1.5	36	6	38
8	EtOH	0.2 M NaOH (20 mol %)	14	83	12	—

[a] Reaction performed at room temperature.
[b] Isolated yield.

as toluene or CH_2Cl_2 (entries 5 and 6) gave an unfavorable ratio of **9** and **10** and even larger amounts of olefin **11** were isolated. Finally, the use of sodium hydroxide at a lower concentration allowed a to rise in the product yield to 83% (entries 7 and 8). No reaction was observed with the Wilkinson catalyst.

The conversion of amine **9** into key-intermediate **3** was performed via acetate **12** (Scheme 6). Nucleophilic substitution at the α-position to ferrocene usually proceeds with complete retention of configuration.[4] Thus, the chiral amine used as an auxiliary in compound **9** was substituted by an acetoxy group upon treatment with acetic anhydride. Acetate **12** reacts with dimethylamine in aqueous solution to give ferrocenyl derivative **3** in excellent yield. Amine **3** was compared to another sample prepared from the alcohol (by CBS-reduction of the corresponding ferrocenyl ketone)[13] and showed essentially the same specific rotation. This proved that our procedure furnishes amine **3** in an enantiomerically pure form as the (*R*)-enantiomer. The overall yield starting from propargylamine **4** was 68% (four steps).

Like Ugi's amine,[14] ferrocenyl amine **3** can undergo a diastereoselective *ortho*-lithiation. This reaction was carried out with *tert*-butyllithium in ether at 0 °C. The reaction with two different chlorophosphines (R^A = Ph, *c*-Hex) and protection[15] led to the borane complexes **13a**,**b** in good yields. Only one diastereomer was observed by NMR spectroscopy (Scheme 7). Unlike JOSIPHOS, these ethyl derivatives can be easily oxidized by air during work-up. Their purification requires a borane protection.

Nucleophilic substitution of amines **13a** and **b** with phosphines (R^B = Ph, *c*-Hex) and protection gave the borane complexes **14a–d**. These stable complexes can be easily handled in air and purified via flash-chromatography.

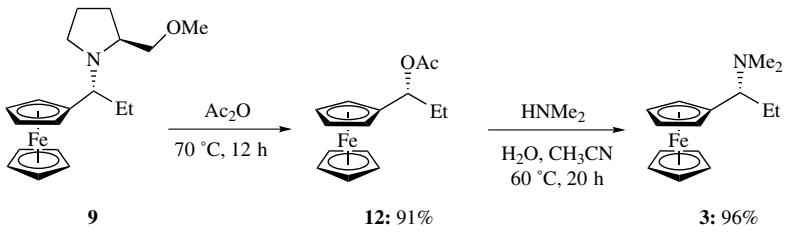
3. Catalysis

Prior to their use as ligands for asymmetric metal catalysis, the borane complexes **14a–d** needed to be deprotected. Since the usual reagents such as diethylamine[16] or DABCO failed to perform this transformation in high yields, we used *N*,*N*′-bis(3-aminopropyl)piperazine **15** at an elevated temperature (100 °C) for the deprotection (Scheme 8).[17]

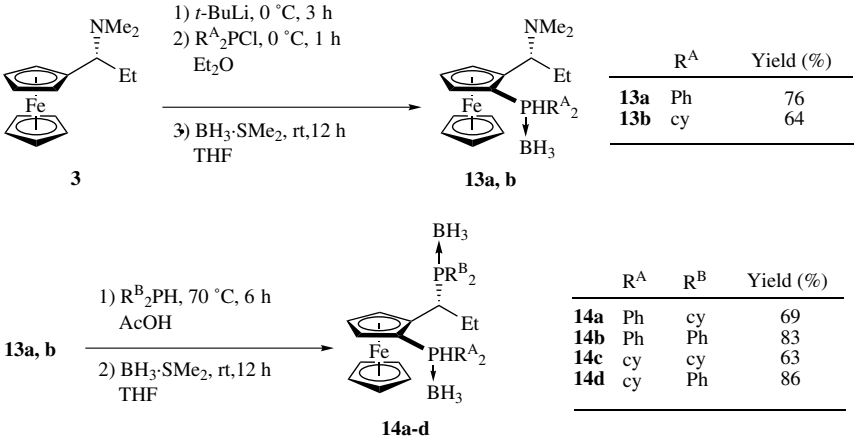
The conversion of borane complexes **14a–d** to the diphosphines **2a–d** was monitored by ^{31}P NMR spectroscopy. After complete deprotection, the amine was removed by filtration through silica under Ar and ligands **2a–d** were obtained in quantitative yield.

We have now examined the scope of ligands **2a–d** in the Rh-catalyzed hydroboration of styrene **16** with catecholborane **17**.[18] After oxidation with aqueous hydrogen peroxide, alcohols **18** and **19** were obtained (Scheme 9 and Table 2).

Surprisingly, the results with ligands **2a–d** indicate that the introduction of an ethyl substituent in JOSIPHOS-type diphosphines decreases the enantioselectivity in the asymmetric Rh-catalyzed hydroboration. The best results were achieved with ligand **2a** (R^A = Ph, R^B = cy,



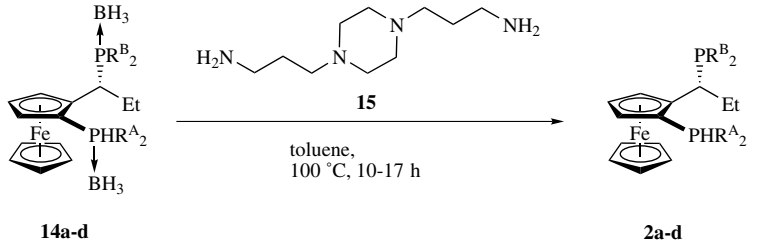
Scheme 6. Substitution of the chiral auxiliary.



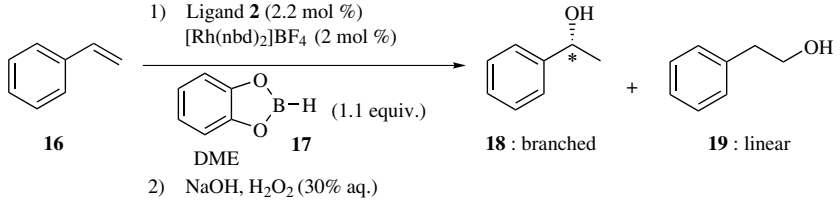
	R^A	Yield (%)
13a	Ph	76
13b	cy	64

	R^A	R^B	Yield (%)
14a	Ph	cy	69
14b	Ph	Ph	83
14c	cy	cy	63
14d	cy	Ph	86

Scheme 7. Synthesis of the ferrocenyl ligands **14a**–**d**.



Scheme 8. Deprotection of ferrocenyl diphosphines **14a**–**d**.



Scheme 9. Asymmetric hydroboration catalyzed by Rh(I)-complexes.

Table 2. Enantioselective hydroboration of styrene

Ligand	Reaction time (h)	Temperature (°C)	Conv.[a] (%)	Regioselectivity[a] **18**:**19**	Enantioselectivity[b] (% ee)
2a	6	−40	71	92:8	46
2b	24	−40	72	53:47	6
2c	20	−40	58	71:29	34
2d	20	−70	52	92:8	15

[a] The ratio of isomers and conversion were determined by GC.
[b] The enantiomeric excess was determined by HPLC (column: Chiracel OD-H). The absolute configuration was established by comparison with literature data.

Table 2, entry 1). Better selectivities were obtained with the JOSIPHOS ligand (65% yield; **18**:**19** > 99:1; 91.5% *ee*).[6a] In analogy with JOSIPHOS, the ligand with R^A = Ph and R^B = cy gave the best results for this reaction. An electron-rich phosphine in the side chain (R^B = cy) proved to be especially important. Thus, with ligands **2b** and **d** (entries 2 and 4) only very low enantioselectivities were obtained, whereas with ligand **2c** (entry 3), a moderate enantioselectivity with a reduced regioselectivity was achieved.

4. Conclusion

In conclusion, we have reported a new and efficient synthesis for JOSIPHOS-type ligands. The diastereoselective three-component reaction avoids the need for resolution processes. Unfortunately, ligands **2a**–**d** did not give as high selectivities as JOSIPHOS **1a** in the Rh-catalyzed hydroboration. Changing the original methyl group to ethyl reduced the performance of the new ligands in asymmetric hydroboration. Further

applications of this approach to prepare ferrocenyl ligands of interest for asymmetric catalysis are underway.

5. Experimental

All reactions were carried out under argon using standard Schlenk techniques. ^{1}H and ^{13}C NMR spectra were recorded on a Bruker AMX 300 instrument. ^{31}P NMR spectra were recorded on a VARIAN Mercury 200 instrument. Chemical shifts (δ) are given as parts per million relative to the residual solvent peak. IR spectra were recorded on a PERKIN ELMER 1420 Infrared Spectrometer. Mass spectra were recorded on a FINNIGAN MAT 95 Q spectrometer. Optical rotations were measured on a PERKIN ELMER 241 polarimeter. Column chromatography was performed on MERCK silica gel 60 (230–400 mesh ASTM). Thin layer chromatography was performed on MERCK TLC-plates silica gel 60 F-254. Enantiomeric excesses were determined by HPLC. A Chiralcel OD-H (Daicel Chemical Industries) column was used with *n*-heptane/*i*-propanol as a mobile phase and detection by a diode array UV–vis detector at 214 nm.

5.1. Diastereoselective three-component reaction

5.1.1. (*R*)-1-Ferrocenyl-1-[(*S*)-2-methoxymethyl-1-pyrrolidinyl]-3-trimethylsilyl-2-propyne 4a. Trimethylsilylacetylene **7a** (1.40 mL, 982 mg, 10.0 mmol), ferrocene carbaldehyde **5** (2.14 g, 10.0 mmol) and (*S*)-2-(methoxymethyl)pyrrolidine **6** (1.23 mL, 1.15 g, 10.0 mmol) were added to a suspension of CuBr (72 mg, 0.5 mmol, 5 mol %) and MS 4 Å (5 g) in toluene (20 mL) at rt. The reaction mixture was stirred at rt and after 5 days the solids were filtered off and washed with diethyl ether. The organic layers were washed with satd NH_4Cl and 25% NH_3 solution (2:1), water, and brine and dried over $MgSO_4$. The crude material was purified by column chromatography (*n*-pentane/triethylamine 20:1). The product **4a** was obtained diastereomerically pure as a red oil (3.03 g, 7.40 mmol, 74%). $[\alpha]_D = +181.9$ (*c* 1.56, $CHCl_3$); IR (KBr): $\tilde{\nu}$ 3096 (m), 2960 (s), 2873 (s), 2825 (m), 2161 (m), 1449 (m), 1249 (s), 1106 (vs), 999 (s), 842 (vs); ^{1}H NMR ($CDCl_3$): δ 4.72 (s, 1H), 4.43 (s, 1H), 4.20 (s, 1H), 4.16 (s, 5H), 4.08 (s, 2H), 3.39 (s, 3H), 3.38 (dd, $J = 9.2$ Hz, 5.9 Hz, 1H), 3.28 (dd, $J = 9.2$ Hz, 6.3 Hz, 1H), 3.11–3.07 (m, 1H), 2.66–2.61 (m, 2H), 1.86–1.80 (m, 1H), 1.67–1.56 (m, 3H), 0.24 (s, 9H); ^{13}C NMR ($CDCl_3$): δ 103.0 (CH), 88.8, 86.1, 76.6, 76.2 (CH_2), 68.6 (CH_3), 68.3 (CH), 67.8 (CH), 67.1 (CH), 59.5 (CH), 58.7 (CH), 53.9 (CH), 48.1 (CH_2), 26.3 (CH_2), 22.5 (CH_2), 0.12 (CH_3); MS (EI, 70 eV) *m*/*z* (%): 410 ($[M+1]^+$, 10), 409 (31), 296 (33), 295 (100); HRMS calcd for $C_{22}H_{31}FeNOSi$: 409.1524. Observed: 409.1544.

5.1.2. (*R*)-1-Ferrocenyl-1-[(*S*)-2-methoxymethyl-1-pyrrolidinyl]-4-methoxy-2-butyne 4b. Prepared according to the procedure described above from methyl propargyl ether **7b** (0.39 mL, 280 mg, 4.0 mmol), ferrocene carbaldehyde **5** (856 mg, 4.0 mmol), (*S*)-2-(methoxymethyl)-pyrrolidine **6** (0.49 mL, 461 mg, 4.0 mmol), CuBr (29 mg, 0.2 mmol, 5 mol %), and MS 4 Å (2 g) in toluene (8 mL). The crude product was purified by column chromatography (*n*-pentane/ether 10:1). Diastereomerically pure **4b** was isolated as a red oil (1.31 g, 3.44 mmol, 86%). $[\alpha]_D = +134.4$ (*c* 4.15, $CHCl_3$); IR (KBr): $\tilde{\nu}$ 3094 (m), 2925 (s), 2874 (s), 2820 (s), 1610 (w), 1449 (m), 1357 (m), 1187 (m), 1106 (vs), 1001 (m), 906 (m), 819 (s), 502 (s); ^{1}H NMR ($CDCl_3$): δ 4.84 (s, 1H), 4.35 (s, 1H), 4.27–4.21 (m, 3H), 4.16 (s, 5H), 4.09 (t, $J = 1.8$ Hz, 2H), 3.47 (s, 3H), 3.41–3.38 (m, 4H), 3.30 (dd, $J = 9.2$ Hz, 5.9 Hz, 1H), 3.10–3.05 (m, 1H), 2.62 (t, $J = 6.6$ Hz, 2H), 1.88–1.79 (m, 1H), 1.67–1.52 (m, 3H); ^{13}C NMR ($CDCl_3$): δ 86.4, 83.3, 80.3 (CH_2), 76.3, 68.6 (CH_3), 68.2 (CH), 67.9 (CH), 67.7 (CH), 67.0 (CH), 59.7 (CH_2), 59.6 (CH_3), 58.7 (CH), 57.0 (CH), 53.2 (CH), 48.1 (CH_2), 28.2 (CH_2), 22.3 (CH_2); MS (EI, 70 eV) *m*/*z* (%): 381 (M^+, 19), 268 (23), 267 (100), 252 (16), 236 (9), 186 (4); HRMS calcd for $C_{21}H_{27}FeNO_2$: 381.1391. Observed: 381.1423.

5.1.3. (*R*)-1-Ferrocenyl-1-[(*S*)-2-methoxymethyl-1-pyrrolidinyl]-4,4-dimethyl-2-pentyne 4c. Prepared according to the procedure described above from 3,3-dimethyl-1-butyne **7c** (0.49 mL, 329 mg, 4.0 mmol), ferrocene carbaldehyde **5** (856 mg, 4.0 mmol), (*S*)-2-(methoxymethyl)pyrrolidine **6** (0.49 mL, 461 mg, 4.0 mmol), CuBr (29 mg, 0.2 mmol, 5 mol %), and MS 4 Å (2 g) in toluene (8 mL). The crude product was purified by column chromatography (*n*-pentane/ether 10:1). Diastereomerically pure **4c** was isolated as a red oil (1.25 g, 3.17 mmol, 80%). $[\alpha]_D = +139.4$ (*c* 0.49, $CHCl_3$); IR (KBr): $\tilde{\nu}$ 3096 (m), 2967 (vs), 2926 (s), 2824 (m), 2226 (w), 1620 (w), 1455 (m), 1361 (m), 1259 (s), 1106 (vs), 1001 (s), 817 (s), 504 (s); ^{1}H NMR ($CDCl_3$): δ 4.65 (s, 1H), 4.34–4.33 (m, 1H), 4.22–4.20 (m, 1H), 4.16 (s, 5H), 4.07 (t, $J = 1.9$ Hz, 2H), 3.38–3.36 (m, 4H), 3.27 (dd, $J = 9.4$ Hz, 6.8 Hz, 1H), 3.11–3.04 (m, 1H), 2.65–2.55 (m, 2H), 1.82–1.77 (m, 1H), 1.66–1.56 (m, 3H), 1.31 (s, 9H); ^{13}C NMR ($CDCl_3$): δ 93.8, 87.7, 76.7 (CH_2), 75.2, 68.9 (CH_3), 68.6 (CH), 68.2 (CH), 68.0 (CH), 67.3 (CH), 59.9 (CH), 59.1 (CH), 53.5 (CH), 48.2 (CH_2), 31.5 (CH_3), 28.9 (CH_2), 27.5, 23.1 (CH_2); MS (EI, 70 eV) *m*/*z* (%): 393 (M^+, 10), 280 (22), 279 (100), 264 (20), 186 (14), 121 (19); HRMS calcd for $C_{23}H_{31}FeNO$: 393.1755. Observed: 393.1764.

5.2. (*R*)-1-Ferrocenyl-1-[(*S*)-2-methoxymethyl-1-pyrrolidinyl]-2-propyne 8

KOH in methanol (1.0 m, 12 mL, 12 mmol, 1.5 equiv) was added to a stirred solution of (*R*)-1-ferrocenyl-1-[(*S*)-2-methoxymethyl-1-pyrrolidinyl]-3-trimethylsilyl-2-propyne **4a** (3.15 g, 7.7 mmol) in methanol (20 mL) at rt. After 1.5 h, the solvent was evaporated, water (30 mL) was added, and the mixture extracted with ether (40 mL). The organic layers were washed with brine and dried over $MgSO_4$. The crude product was purified by column chromatography (*n*-pentane/diethyl ether 3:2). The product **8** was isolated as a red solid (2.43 g, 7.21 mmol, 94%). Mp 44.5–45.5 °C; $[\alpha]_D = +87.3$ (*c* 3.29, $CHCl_3$); IR (KBr): $\tilde{\nu}$ 3296 (s), 3096 (m), 2960 (s), 2873 (s), 2826 (m), 1450 (m), 1233 (m), 1193 (m), 1106 (m), 1001 (m), 820 (m); ^{1}H NMR ($CDCl_3$): δ 4.83 (d,

$J = 2.0$ Hz, 1H), 4.36 (dd, $J = 3.2$ Hz, 1.6 Hz, 1H), 4.25 (s, br, 1H), 4.10 (s, 5H), 4.08 (t, $J = 1.9$ Hz, 2H), 3.47 (dd, $J = 12.1$ Hz, 6.0 Hz, 1H), 3.39 (s, 3H), 3.33 (dd, $J = 10.2$ Hz, 5.9 Hz, 1 H), 3.13–3.04 (m, 1H), 2.64–2.60 (m, 2H), 2.41 (d, $J = 2.2$ Hz, 1 H), 1.89–1.83 (m, 1H), 1.68–1.56 (m, 3H); ^{13}C NMR ($CDCl_3$): δ 86.4, 80.6, 76.8 (CH), 72.9 (CH), 69.1 (CH_3), 68.9 (CH), 68.6 (CH), 68.2 (CH), 67.5 (CH), 59.9 (CH), 59.1 (CH), 53.4 (CH), 48.3 (CH_2), 28.5 (CH_2), 22.7 (CH_2); MS (EI, 70 eV) m/z (%): 338 (M^+, 2), 337 (10), 223 (100), 120 (19); HRMS calcd for $C_{19}H_{23}FeNO$: 337.1129. Observed: 337.1100.

5.3. (*R*)-1-Ferrocenyl-1-[(*S*)-2-methoxymethyl-1-pyrrolidinyl]-2-propane 9

A mixture of (*R*)-1-ferrocenyl-1-[(*S*)-2-methoxymethyl-1-pyrrolidinyl]-2-propyne **8** (674 mg, 2.00 mmol), NaOH in ethanol (0.2 m, 2 mL, 0.4 mmol, 20 mol %), and palladium on charcoal (10%, 24 mg) in ethanol (4 mL) was stirred at rt under a hydrogen atmosphere (1 bar) for 14 h. The reaction mixture was filtered. After removal of the solvent, the crude product was purified by column chromatography (*n*-pentane/diethyl ether 2:1 + 0.5% NEt_3). The product **9** was obtained as a red oil (574 mg, 1.68 mmol, 83%). $[\alpha]_D = -61.8$ (*c* 0.86, $CHCl_3$); IR (KBr): $\tilde{\nu}$ 3094 (m), 2959 (s), 2928 (s), 2872 (s), 1674 (m), 1453 (m), 1383 (w), 1195 (w), 1106 (vs), 1057 (s), 1001 (w), 817 (m); ^{1}H NMR ($CDCl_3$): δ 4.10–4.08 (m, 1H), 4.06–4.00 (m, 8H), 3.47 (dd, $J = 9.4$ Hz, 4.0 Hz, 1H), 3.29 (s, 3H), 3.14 (dd, $J = 9.7$ Hz, 4.3 Hz, 1H), 3.00 (t, $J = 8.6$ Hz, 1H), 2.70–2.60 (m, 2H), 2.01–1.89 (m, 2H), 1.79–1.34 (m, 5H), 1.05 (t, $J = 7.4$ Hz, 3H); ^{13}C NMR ($CDCl_3$): δ 90.2, 77.4 (CH), 77.2 (CH_2), 68.53 (CH_3), 68.52 (CH), 67.06 (CH), 67.05 (CH), 61.4 (CH), 58.9 (CH), 57.2 (CH), 51.0 (CH_2), 29.0 (CH_2), 25.7 (CH_2), 23.8 (CH_2), 12.5 (CH_3); MS (EI, 70 eV) m/z (%): 341 (M^+, 15), 315 (15), 312 (84), 290 (48), 246 (13), 227 (100), 212 (30), 186 (24), 121 (44); HRMS calcd for $C_{19}H_{27}FeNO$: 341.1442. Observed: 341.1459.

5.4. (*R*)-[3-(*N*,*N*-Dimethylamino)propyl]ferrocene 3

A solution of (*R*)-1-ferrocenyl-1-[(*S*)-2-methoxymethyl-1-pyrrolidinyl]-2-propane **9** (682 mg, 2.00 mmol) in freshly distilled acetic anhydride (10 mL) was stirred for 12 h at 70 °C. The reaction mixture was cooled to 0 °C and water added carefully. The mixture was neutralized with 2 M NaOH solution and extracted with ether (40 mL). The organic layers were washed with water and brine and dried over $MgSO_4$. The solvents were distilled off and the product dried under vacuum (10^{-3} mbar). The acetamido derivative of the chiral auxiliary was efficiently removed during work-up. No attempts were made to isolate it. The remaining acetate **12** (521 mg, 1.82 mmol) was dissolved in acetonitrile (6 mL) without further purification. Dimethylamine (6 mL, 40% solution in water) was added and the reaction mixture stirred for 20 h at 60 °C in a sealed tube. After purification by acid–base work-up, amine **3** was obtained as a yellow solid (471 mg, 1.73 mmol, 87% over two steps). mp 66.0–67.5 °C; $[\alpha]_D = -57.5$ (*c* 0.5, $CHCl_3$); ^{1}H NMR ($CDCl_3$): δ 4.05–3.97 (m, 8H), 3.96–3.94 (m, 1H), 3.18 (dd, $J = 11.0$ Hz, 3.4 Hz, 1H), 2.03–1.89 (m, 1H), 1.93 (s, 6 H), 1.73–1.57 (m, 1H), 1.03 (t, $J = 7.4$ Hz, 3H); ^{13}C NMR ($CDCl_3$): δ 85.6, 69.3 (CH), 68.5 (CH), 67.4 (CH), 67.1 (CH), 66.8 (CH), 64.9 (CH), 40.5 (CH_3), 24.4 (CH_2), 12.3 (CH_3); HRMS calcd for $C_{15}H_{21}FeN$: 271.1023. Observed: 271.1003. Further analytical data is in accordance with the literature.[13]

5.5. Synthesis of the protected monophosphines 13a,b

5.5.1. (S_{Fc})-1-Diphenylphosphano-2-[α-(*R*)-(*N*,*N*-dimethylamino)propyl]ferrocene borane complex 13a. A solution of (*R*)-[3-(*N*,*N*-dimethylamino)propyl]ferrocene **3** (204 mg, 0.75 mmol) in diethyl ether (6 mL) was cooled to 0 °C. *tert*-BuLi in pentane (1.45 m, 0.57 mL, 0.82 mmol, 1.1 equiv) was added dropwise and the mixture stirred for 3 h at 0 °C. Chlorodiphenylphosphine (0.17 mL, 0.97 mmol, 1.3 equiv) was added at 0 °C. The reaction mixture was stirred for 1 h at rt, then a borane dimethyl sulfide complex (0.70 mL, 0.75 mmol, 10 equiv) added dropwise and the mixture stirred for 13 h at rt. After careful addition of water, the mixture was extracted with CH_2Cl_2 (30 mL) and the organic layers washed with water and brine and dried over $MgSO_4$. The crude product was purified by column chromatography (*n*-pentane/CH_2Cl_2 2:3). Compound **13a** was obtained as an orange solid (267 mg, 0.569 mmol, 76%). Mp 204.2–205.1 °C (decomp.); $[\alpha]_D = -304.7$ (*c* 0.54, CH_2Cl_2); IR: (Film): $\tilde{\nu}$ 3436 (s), 2388 (m), 1629 (w), 1437 (m), 1173 (m), 1063 (m), 823 (m), 743 (m), 699 (m); ^{1}H NMR ($CDCl_3$): δ 7.87–7.50 (m, 4H), 7.48–7.35 (m, 6H), 4.84 (s, br, 1H), 4.61 (s, br, 1H), 4.30 (s, br, 1H), 4.19 (s, br, 1H), 3.94 (s, 5H), 2.59–2.45 (m, 1H), 2.24–2.18 (m, 1H), 2.15 (s, 3H), 1.83 (s, 3H), 1.70 (s, br, 3H), 1.35 (t, $J = 7.6$ Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$): δ 133.8 (CH), 133.6 (CH), 132.9 (CH), 132.8 (CH), 131.5 (CH), 131.4 (CH), 131.2, 130.3, 129.0 (CH), 128.9 (CH), 128.8 (CH), 128.6 (CH), 74.5 (CH), 73.4 (CH), 72.2 (CH), 71.7, 71.5 (CH), 69.2 (CH), 53.1 (CH_3), 50.0 (CH_3), 28.9 (CH_2), 16.0 (CH_3); ^{31}P NMR (81 MHz, $CDCl_3$): δ +10.8 (s, br); MS (EI, 70 eV) m/z (%): 469 (M^+, 2), 455 (49), 440 (19), 426 (100), 412 (32), 226 (42), 183 (32), 121 (34); HRMS calcd for $C_{27}H_{33}BFeNP$: 469,1793. Observed: 469.1802.

5.5.2. (S_{Fc})-1-Dicyclohexylphosphano-2-[α-(*R*)-(*N*,*N*-dimethylamino)propyl]ferrocene borane complex 13b. Prepared according to the procedure described above from (*R*)-[3-(*N*,*N*-dimethylamino)propyl]ferrocene **3** (196 mg, 0.72 mmol), *tert*-BuLi (1.45 m, 0.55 mL, 0.79 mmol, 1.1 equiv), chlorodicyclohexylphosphine (0.2 mL, 0.94 mmol, 1.3 equiv), and borane dimethyl sulfide complex (0.70 mL, 0.73 mmol, 10 equiv). The crude product was purified by column chromatography (*n*-pentane/CH_2Cl_2 2:3). Compound **13b** was obtained as an orange solid (222 mg, 0.461 mmol, 64%). Mp 166–167.5 °C (decomp.); $[\alpha]_D = -144.8$ (*c* 0.29, CH_2Cl_2); IR (KBr): $\tilde{\nu}$ 3436 (w), 2931 (s), 2852 (m), 2388 (s), 1636 (w), 1449 (m), 1173 (m), 1064 (m), 822 (m); ^{1}H NMR ($CDCl_3$): δ 4.71 (s, br, 1H), 4.66 (s, br, 2H), 4.34 (s, 5H), 3.76 (s, br, 1H), 2.66–2.52 (m, 1H), 2.40 (s, 3H), 2.34 (s,

3H), 2.29–1.01 (m, 26H), 1.46 (t, $J = 7.6$ Hz, 3H); ^{13}C NMR ($CDCl_3$): δ 76.5 (CH), 74.7, 74.1, 73.4 (CH), 73.1 (CH), 71.8 (CH), 53.9 (CH_3), 48.7 (CH_3), 37.1 (CH, d, $J = 30.4$ Hz), 32.3–28.1 (m, CH_2), 18.2 (CH_3); ^{31}P NMR (81 MHz, $CDCl_3$): δ +27.6 (s, br); MS (EI, 70 eV) m/z (%): 481 (M^+, 15), 467 (31), 452 (89), 424 (61), 384 (52), 341 (52), 259 (100), 226 (58), 121 (22); HRMS calcd for $C_{27}H_{45}BFeNP$: 481.2732. Observed: 481.2734.

5.6. Synthesis of the protected diphosphines 14a–d

5.6.1. (S_{Fc})-1-Diphenylphosphano-2-[α-(*R*)-(dicyclohexylphosphano)propyl]ferrocene bis-borane complex 14a. Dicyclohexylphosphine (40 mg, 0.20 mmol, 1.2 equiv) was added to a solution of **13a** (80 mg, 0.17 mmol) in degassed acetic acid (3.5 mL). The mixture was heated to 60 °C for 6 h. After the mixture had been cooled to rt, the solvent was removed under reduced pressure and the residual oil dissolved in THF (2 mL). Borane dimethyl sulfide complex (0.16 mL, 1.7 mmol, 10 equiv) was added dropwise and the mixture stirred for 14 h at rt. After careful addition of water, the mixture was extracted with CH_2Cl_2 (20 mL) and the organic layers were washed with water and brine and dried over $MgSO_4$. The crude product was purified by column chromatography (*n*-pentane/CH_2Cl_2 3:2). Compound **14a** was obtained as an orange solid (75 mg, 0.112 mmol, 69%). Mp 230.3–232.6 °C (decomp.); $[\alpha]_D = -196.4$ (*c* 0.39, CH_2Cl_2); IR: (KBr): $\tilde{\nu}$ 3436 (w), 2931 (s), 2390 (m), 1630 (w), 1437 (m), 1062 (m), 741 (m), 698 (m); ^{1}H NMR ($CDCl_3$): δ 7.79–7.70 (m, 4H), 7.43–7.19 (m, 6H), 4.85 (s, br, 1H), 4.48 (t, $J = 2.6$ Hz, 1H), 4.16 (s, br, 1H), 3.91 (s, 5H), 3.33–3.25 (m, 1H), 2.34–2.22 (m, 2H), 1.95–0.42 (m, 28H), 1.37 (t, $J = 7.2$ Hz, 3H); ^{13}C NMR ($CDCl_3$): δ 133.6 (CH), 133.5 (CH), 133.4 (CH), 133.3 (CH), 131.9, 131.5, 131.3 (CH), 129.1 (CH), 129.0 (CH), 128.7 (CH), 128.6 (CH), 74.1 (CH), 72.4 (CH), 71.2 (CH), 70.8 (CH), 68.8, 68.0, 34.1 (CH, d, $J = 28.2$ Hz), 32.0 (CH, d, $J = 28.0$ Hz), 29.3 (CH, d, $J = 26.5$ Hz), 28.6–25.9 (CH_2, m), 15.3 (CH_3, d, $J = 8.1$ Hz); ^{31}P NMR ($CDCl_3$): δ +41.6 (s, br), +10.5 (s, br); MS (EI, 70 eV) m/z (%): 636 (M^+, 0.2), 621 (6), 525 (100), 411 (80), 226 (30); HRMS calcd for $C_{37}H_{52}B_2FeP_2$: 636.3080. Observed: 636.3045.

5.6.2. (S_{Fc})-1-Diphenylphosphano-2-[α-(*R*)-(diphenylphosphano)propyl]ferrocene bis-borane complex 14b. Prepared according to the procedure described above from **13a** (96 mg, 0.20 mmol) and dicyclohexylphosphine (45 mg, 0.24 mmol, 1.2 equiv). The crude product was purified by column chromatography (*n*-pentane/CH_2Cl_2 3:2). Compound **14b** was isolated as a red solid (104 mg, 0.167 mmol, 83%). Mp 222.1–224.3 °C (decomp.); $[\alpha]_D = -212.1$ (*c* 0.43, CH_2Cl_2); IR (KBr): $\tilde{\nu}$ 3438 (w), 2379 (m), 1636 (w), 1438 (m), 1104 (m), 1060 (m), 744 (m), 699 (s); ^{1}H NMR ($CDCl_3$): δ 8.05–7.96 (m, 2H), 7.76–7.66 (m, 2H), 7.46–7.18 (m, 14H), 6.81–6.78 (m, 2H), 5.15 (s, br, 1H), 4.44 (t, $J = 2.6$ Hz, 1H), 4.31 (dt, $J = 6.5$ Hz, 5.4 Hz, 1H), 4.30 (s, br, 1H), 3.79 (s, 5H), 2.44–2.17 (m, 2H), 1.35 (s, br, 6H), 1.02 (t, $J = 7.6$ Hz, 3H); ^{13}C NMR ($CDCl_3$): δ 133.6–128.0 (m), 72.7 (CH), 72.1 (CH), 71.1 (CH), 67.7 (d, $J = 3.5$ Hz), 66.8 (d, $J = 3.5$ Hz), 32.5 (CH_2, d, $J = 19.9$ Hz), 15,2 (CH_3, d, $J = 6.6$ Hz); ^{31}P NMR ($CDCl_3$): δ +26.3 (s, br), +12.5 (s, br); MS (EI, 70 eV) m/z (%): 624 (M^+, 0.3), 596 (15), 411 (91), 334 (11), 226 (100), 183 (17), 108 (11); HRMS calcd for $C_{37}H_{40}B_2FeP_2$: 624.2141. Observed: 624.2179.

5.6.3. (S_{Fc})-1-Dicyclohexylphosphano-2-[α-(*R*)-(dicyclohexylphosphano)propyl]ferrocene bis-borane complex 14c. Prepared according to the procedure described above from **13b** (86 mg, 0.18 mmol) and diphenylphosphine (45 mg, 0.22 mmol, 1.2 equiv). The crude product was purified by column chromatography (*n*-pentane/CH_2Cl_2 3:2). Compound **14c** was isolated as an orange solid (73 mg, 0.113 mmol, 63%). Mp 118.3–122.4 °C (decomp.); $[\alpha]_D = -29.9$ (*c* 0.36, CH_2Cl_2); IR (KBr): $\tilde{\nu}$ 3436 (w), 2930 (s), 2852 (m), 2385 (m), 1630 (m), 1449 (m), 1062 (m), 1003 (m), 824 (m); ^{1}H NMR ($CDCl_3$): δ 5.01 (s, br, 1H), 4.41 (t, $J = 2.3$ Hz, 1H), 4.22 (s, br, 1H), 4.18 (s, 5H), 3.32 (ddd, $J = 10.6$ Hz, 6.6 Hz, 4.0 Hz, 1H), 2.35–0.76 (m, 52H), 1.32 (t, $J = 7.5$ Hz, 3H); ^{13}C NMR ($CDCl_3$): δ 70.4, 70.2 (CH), 69.7 (CH), 69.2 (CH), 69.0, 52.1, 38.5 (CH, d, $J = 33.5$ Hz), 35.4 (CH, d, $J = 34.0$ Hz), 34.2 (CH, d, $J = 27.9$ Hz), 33.2 (CH, d, $J = 28.0$ Hz), 31.4–24.5 (m), 13.5 (CH_3); ^{31}P NMR ($CDCl_3$): δ +39.8 (s, br), +22.6 (s, br); MS (EI, 70 eV) m/z (%): 648 (M^+, 0.2), 633 (6), 537 (100), 371 (52), 289 (6), 257 (9), 121 (2); HRMS calcd for $C_{37}H_{64}B_2FeP_2$: 648.4019. Observed: 648.4025.

5.6.4. (S_{Fc})-1-Dicyclohexylphosphano-2-[α-(*R*)-(diphenylphosphano)propyl]ferrocene bis-borane complex 14d. Prepared according to the procedure described above from **13b** (80 mg, 0.16 mmol) and diphenylphosphine (40 mg, 0.20 mmol, 1.2 equiv). The crude product was purified by column chromatography (*n*-pentane/CH_2Cl_2 3:2). Compound **14d** was isolated as a red solid (87 mg, 0.136 mmol, 86%). Mp 175 °C (decomp.); $[\alpha]_D = -44.4$ (*c* 0.27, CH_2Cl_2); IR (KBr): $\tilde{\nu}$ 3435 (w), 2930 (s), 2851 (m), 2383 (s), 1637 (w), 1437 (s), 1060 (s), 736 (m), 700 (s); ^{1}H NMR (C_6D_6): δ 8.05–7.90 (m, 4H), 7.18–7.12 (m, 6H), 5.19 (s, br, 1H), 4.27 (s, br, 1H), 3.90 (s, 5H), 3.87–3.79 (m, 1H), 2.78–2.62 (m, 1H), 2.51–2.31 (m, 2H), 2.19–0.63 (m, 28H), 1.73 (t, $J = 7.1$ Hz, 3H); ^{13}C NMR ($CDCl_3$): δ 134.0, 133.9 (CH), 133.7 (CH), 133.6 (CH), 131.3 (CH), 131.2 (CH), 129.2 (CH), 129.6, 129.4, 129.1 (CH), 128.7 (CH), 128.6 (CH), 72.9 (CH), 70.7 (CH), 69.8 (CH), 69.4 (CH), 67.3, 66.5, 33.0 (CH, d, $J = 27.5$ Hz), 31.5 (CH, d, $J = 28.2$ Hz), 30.6 (CH), 28.2 (CH, d, $J = 24.1$ Hz), 27.2 (CH, d, $J = 35.8$ Hz), 26.6–24.6 (m), 14.0 (CH_3); ^{31}P NMR ($CDCl_3$): δ +26.4 (s, br), +22.4 (s, br); MS (EI, 70 eV) m/z (%): 636 (M^+, 0.2), 621 (4), 525 (100), 442 (8), 423 (12), 257 (18), 226 (12); HRMS calcd for $C_{37}H_{52}B_2FeP_2$: 636.3080. Observed: 636.3116.

5.7. Deprotection

Prior to use in catalysis, the required quantity of the protected ligand **14a–d** (12–15 mg) was dissolved in toluene (0.8 mL). To the solution, 1,4-bis(3-aminopropyl)piperazine (**15**, 45–50 mg, excess) was added. The reaction mixture was heated at 100 °C for 10–17 h, cooled and

diluted with ether (5–10 mL). The solution was filtered under an Ar atmosphere through a pad of previously dried silica gel. Solvents were removed under vacuum. The deprotection can be monitored by ^{31}P NMR.

5.7.1. (S_{Fc})-1-Diphenylphosphano-2-[α-(*R*)-(dicyclohexylphosphano)propyl]ferrocene 2a. ^{31}P NMR (Et_2O): δ +21.7 (d, $J = 21$ Hz), −24.7 (d, $J = 21$ Hz).

5.7.2. (S_{Fc})-1-Diphenylphosphano-2-[α-(*R*)-(diphenylphosphano)propyl]ferrocene 2b. ^{31}P NMR (Et_2O): δ +3.1 (d, $J = 14$ Hz), −24.4 (d, $J = 14$ Hz).

5.7.3. (S_{Fc})-1-Dicyclohexylphosphano-2-[α-(*R*)-(dicyclohexylphosphano)propyl]ferrocene 2c. ^{31}P NMR (Et_2O): +13.1 (d, $J = 16$ Hz), −14.7 (d, $J = 16$ Hz).

5.7.4. (S_{Fc})-1-Dicyclohexylphosphano-2-[α-(*R*)-(diphenylphosphano)propyl]ferrocene 2d. ^{31}P NMR (Et_2O): +21.0 (d, $J = 22$ Hz), −25.8 (d, $J = 22$ Hz).

5.8. Hydroboration of styrene

The freshly deprotected ligand **2a**–**d** and $[Rh(nbd)_2]BF_4$ (7.5 mg, 0.020 mmol, 2 mol %) were dissolved in DME (2 mL) and stirred for 20 min at rt. Styrene **16** (0.11 mL, 1.0 mmol) and tetradecane as internal standard were added and the mixture cooled to the indicated temperature (Table 2) before catechol borane **17** (0.11 mL, 1.1 mmol) was added. The reaction was followed by GC. Aliquots were treated with a mixture of 2 M sodium hydroxide solution and hydrogen peroxide solution (30%). After the indicated time (Table 2) methanol (1 mL), 2 M sodium hydroxide solution (1.5 mL), and hydrogen peroxide solution (30%, 0.1 mL) were added subsequently to the reaction mixture. The mixture was warmed up to rt and then extracted with diethyl ether (60 mL) and the organic layers washed with 1 M sodium bisulfite solution, water, and brine and dried over $MgSO_4$. The crude product was dissolved in diethyl ether and filtered through a short pad of silica gel. The enantiomeric excess was determined by HPLC (OD-H, 95% *n*-heptane, 5% *i*-propanol, 0.6 mL/min); retention time (min): 1-phenylethanol: 15.0 (*R*), 17.5 (*S*); 2-phenylethanol: 16.1.

Acknowledgements

We thank Degussa AG (Frankfurt) for generous support, S.Y. thanks the Humboldt Foundation for a fellowship, N.G. thanks the DFG (SPP 1118 'Sekundäre Wechselwirkungen als Steuerungsprinzip zur gerichteten Funktionalisierung reaktionsträger Substrate') and R.J.K. thanks the Stiftung Stipendien-Fonds des VCI (Frankfurt) and the Bundesministerium für Bildung und Forschung for a scholarship.

References

1. Noyori, R. *Asymmetric Catalysis in Organic Synthesis*; John Wiley & Sons: New York, 1994.
2. (a) Togni, A.; Hayashi, T. *Ferrocenes: Homogeneous Catalysis, Organic Synthesis, Material Science*; VCH: Weinheim, 1995; (b) Perseghini, M.; Togni, A. *Sci. Synth.* **2002**, *1, 889.*
3. For recent reviews see: (a) Atkinson, R. C. J.; Gibson, V. C.; Long, N. J. *Chem. Soc. Rev.* **2004**, *33*, 313; (b) Colacot, T. J. *Chem. Rev.* **2003**, *103*, 3101; for further examples see: (c) Sturm, T.; Weissensteiner, W.; Spindler, F. *Adv. Synth. Catal.* **2003**, *345*, 160; (d) Ireland, T.; Grossheimann, G.; Wieser-Jeunesse, C.; Knochel, P. *Angew. Chem., Int. Ed.* **1999**, *38*, 3212; (e) Lotz, M.; Polborn, K.; Knochel, P. *Angew. Chem., Int. Ed.* **2002**, *41*, 4708; (f) Lotz, M.; Kramer, G.; Knochel, P. *Chem. Commun.* **2002**, 2546; (g) Almena Perea, J. J.; Lotz, M.; Knochel, P. *Tetrahedron: Asymmetry* **1999**, *10*, 375; (h) Enders, D.; Peters, R.; Lochtman, R.; Raabe, G.; Runsink, J.; Bats, J. W. *Eur. J. Org. Chem.* **2002**, 3399; (i) Berens, U.; Burk, M. J.; Gerlach, A.; Hems, W. *Angew. Chem., Int. Ed.* **2000**, *39*, 1981.
4. (a) Gokel, G. W.; Marquarding, D.; Ugi, I. K. *J. Org. Chem.* **1972**, *37*, 3052; (b) Gokel, G.; Hoffmann, P.; Klusacek, H.; Marquarding, D.; Ugi, I. *Angew. Chem.* **1970**, *82*, 77.
5. Hayashi, T.; Mise, T.; Mitachi, S.; Yamamoto, K.; Kumada, M. *Tetrahedron Lett.* **1976**, *17*, 1133.
6. (a) Togni, A.; Breutel, C.; Schnyder, A.; Spindler, F.; Landert, H.; Tijani, A. *J. Am. Chem. Soc.* **1994**, *116*, 4062; (b) Togni, A. *Angew. Chem.* **1996**, *108*, 1581; (c) Togni, A.; Bieler, N.; Burckhardt, U.; Köllner, C.; Pioda, G.; Schneider, R.; Schnyder, A. *Pure Appl. Chem.* **1999**, *71*, 1531.
7. J. McGarrity, F. Spindler, R. Fuchs, M. Eyer (Lonza AG), EP-A624587A2, 1995.
8. Spindler, F.; Pugin, B.; Jalett, H.-P.; Buser, H.-P.; Pittelkow, U.; Blaser, H. U. (Novartis AG) *Chem. Ind. (Dekker)* **1996**, *68*, 153.
9. (a) López, F.; Harutyunyan, S. R.; Meetsma, A.; Minaard, A. J.; Feringa, B. L. *Angew. Chem., Int. Ed.* **2005**, *44*, 2752; (b) Lipshutz, B. H.; Servesko, J. M.; Taft, B. R. *J. Am. Chem. Soc.* **2004**, *126*, 8352; (c) Lipshutz, B. H.; Servesko, J. M. *Angew. Chem., Int. Ed.* **2003**, *42*, 4789.
10. (a) Gommermann, N.; Koradin, C.; Polborn, K.; Knochel, P. *Angew. Chem., Int. Ed.* **2003**, *42*, 5763; (b) Dube, H.; Gommermann, N.; Knochel, P. *Synthesis* **2004**, 2015; (c) Gommermann, N.; Knochel, P. *Chem. Commun.* **2004**, 2324.
11. Hayashi, T.; Mise, T.; Fukushima, M.; Kagotani, M.; Nagashima, N.; Hamada, Y.; Matsumoto, A.; Kawakami, S.; Konishi, M. *Bull. Chem. Soc. Jpn.* **1980**, *53*, 1138.
12. Corey, E. J.; Gross, A. W. *Tetrahedron Lett.* **1984**, *25*, 495.
13. Tappe, K.; Knochel, P. *Tetrahedron: Asymmetry* **2004**, *15*, 91.
14. (a) Marquarding, D.; Klusacek, H.; Gokel, G.; Hoffmann, P.; Ugi, I. *J. Am. Chem. Soc.* **1970**, *92*, 5389; (b) Ohno, A.; Yamane, M.; Hayashi, T. *Tetrahedron: Asymmetry* **1995**, *6*, 2495.
15. Pellon, P. *Tetrahedron Lett.* **1992**, *33*, 4451.
16. Imamoto, T.; Kusumoto, T.; Suzuki, N.; Sato, K. *J. Am. Chem. Soc.* **1985**, *107*, 5301.
17. Gavryushin, A.; Polborn, K.; Knochel, P. *Tetrahedron: Asymmetry* **2004**, *15*, 2279.
18. For general reviews see: (a) Carroll, A.-M.; O'Sullivan, T. P.; Guiry, P. J. *Adv. Synth. Catal.* **2005**, *347*, 609; (b) Chelucci, G.; Orrù, G.; Pinna, G. *Tetrahedron* **2003**, *59*, 9471; (c) Beletskaya, I.; Pelter, A. *Tetrahedron* **1997**, *53*, 4957; For further examples: (d) Knöpfel, T. F.; Aschwanden, P.; Ichikawa, T.; Watanabe, T.; Carreira, E. M. *Angew. Chem., Int. Ed.* **2004**, *43*, 5971; (e) Segarra, A. M.; Claver, C.; Fernandez, E. *Chem. Commun.* **2004**, 464; (f)

Kwong, F. Y.; Yang, Q.; Mak, T. C. W.; Chan, A. S. C.; Chan, K. S. *J. Org. Chem.* **2002**, *67*, 2769; (g) Demay, S.; Volant, F.; Knochel, P. *Angew. Chem., Int. Ed.* **2001**, *40*, 1235; (h) Fernandez, E.; Maeda, K.; Hooper, M. W.; Brown, J. M. *Chem. Eur. J.* **2000**, *6*, 1840; (i) Reetz, M. T.; Beuttenmuller, E. W.; Goddard, R.; Pasto, M. *Tetrahedron Lett.* **1999**, *40*, 4977; (j) Doucet, H.; Fernandez, E.; Layzell, T. P.; Brown, J. M. *Chem. Eur. J.* **1999**, *5*, 1320.