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Synthesis of α,β-disubstituted ferrocenes via a ferrocenylepoxide intermediate. Preparation and catalytic activity of a new chiral ferrocenyloxazoline

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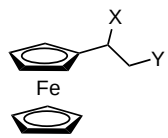
Abstract—A short synthesis of the chiral oxazoline **10** (>95% e.e.) in six steps from chloroacetylferrocene is described. The ligand can be used successfully in an asymmetric Pd(0)-catalyzed allylic alkylation reaction. © 2002 Elsevier Science Ltd. All rights reserved.

1. Introduction

Chiral ferrocene derivatives have found widespread applications as ligands for asymmetric synthesis in homogeneous phase.[1] The peculiar features of ferrocene chemistry, especially the retentive nucleophilic substitution of heteroatomic α-substituents[2] and the diastereoselective *ortho*-directed metalation of starting chiral ferrocenyl derivatives,[3] have allowed the preparation of a large number of 1,1′- or 1,2-disubstituted ferrocenyl ligands possessing suitable groups for coordination with different transition metals.[4]

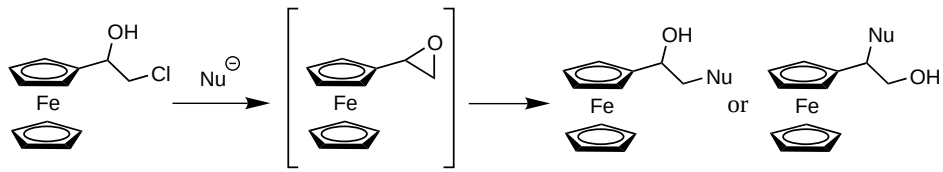
However, relatively few examples of disubstituted ferrocenes of the type **1** have been reported[5] and recently the diol **1a** has been prepared in both enantiomeric forms by asymmetric dihydroxylation of vinylferrocene.[6]



1

1a X=Y=OH

Ferrocenylepoxide **2** can be considered a useful starting material for the preparation of this class of difunctionalised ferrocenes, but to date methods to prepare **2** either in racemic or scalemic forms have not been reported. In this context we envisaged that ferrocenylalcohol **3** could act as a precursor of epoxide **2** in the presence of basic nucleophilic reagents that would also promote the in situ opening of the oxirane ring giving access to α,β-disubstituted ferrocenes (see Scheme 1).



3 **2**

Scheme 1.

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Herein, we report the application of this strategy for the preparation of some chiral ferrocenyl derivatives. Thus, asymmetric reduction of chloroacetylferrocene **4** gave (*R*)-**3** that was converted into the amino alcohol (*R*)-**5** with retention of configuration. (*R*)-**5** was in turn converted into a new ferrocenyloxazoline, which proved to be an efficient catalyst for the Pd-catalyzed asymmetric allylic substitution reaction.[7]

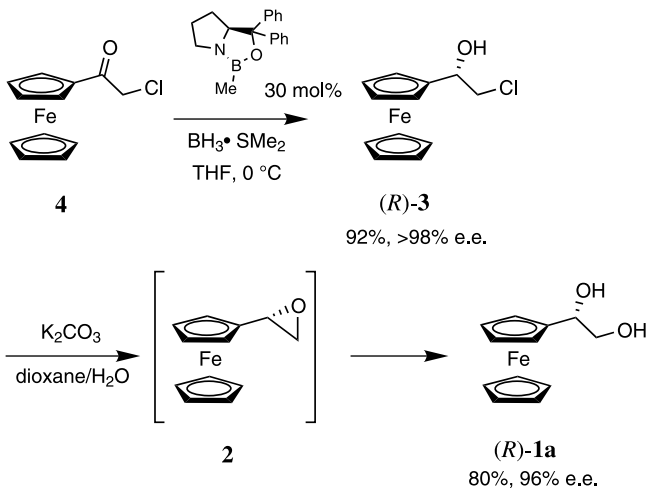
2. Results and discussion

2.1. Synthesis of α,β-disubstituted ferrocenes

Ferrocenylalcohol (*R*)-**3** was readily obtained in high enantiomeric purity by the asymmetric reduction of chloroacetylferrocene **4** in the presence of (*S*)-CBS catalyst (30 mol%) and $BH_3{\cdot}SMe_2$ as the hydride source. The reaction was carried out as previously described[8] affording (*R*)-(−)-**3** in >98% e.e. and nearly quantitative yield (Scheme 2).

Treatment of (*R*)-**3** with K_2CO_3 in a dioxane/water (4:1) solution at room temperature for 12 h gave the known diol (*R*)-**1a**[6] with about the same enantiomeric excess as the starting alcohol. As 2-chloroethylferrocene was unreactive under these conditions, it can be assumed that the formation of (*R*)-**1a** from (*R*)-**3** occurs through the opening of the intermediate ferrocenylepoxide **2** (Scheme 2).

The reaction of the hydroxy chloride (*R*)-**3** with excess aqueous 30% NH_4OH at 50°C for 4 h and then at room temperature overnight afforded ferrocenyl amino alcohol (−)-**5** in about 70% yield without any loss of enantiomeric purity (Scheme 3). The known isomeric amino alcohol[5] bearing the amino group at the β-position was not detected. Thus, the nitrogen nucleophile attacks the intermediate epoxide in a highly regioselective manner at the α-position. This selectivity, similar to that observed in phenyl-α,β-epoxides, can be ascribed to the pseudobenzylic character of the carbon in the position α to the ferrocene moiety. In the case of β,γ-ferrocenylepoxides 'normal' opening of the oxirane ring at the terminal and less hindered position has been reported.[9]



Scheme 2.

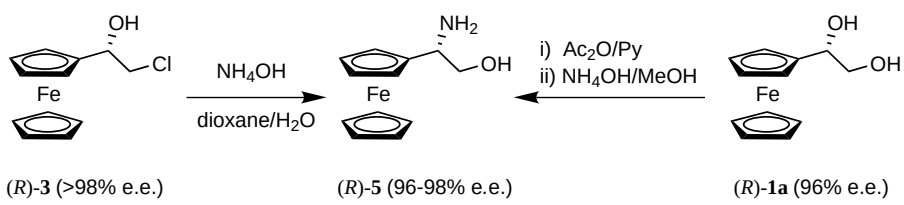
This observed regioselectivity and the stereochemical outcome of the reaction yielding (*R*)-**1a** led us to deduce that the opening of the intermediate ferrocenylepoxide proceeded with complete retention of configuration in agreement with the known reaction course of nucleophilic substitutions at the α-ferrocenylic position, so that (*R*)-configuration was assigned to (−)-**5** and confirmed by chemical correlation with diol (*R*)-**1a**.

It should be noted that secondary amines (diisopropylamine or piperidine) showed very low reactivity, presumably due to steric reasons, and by reaction with (*R*)-**3** the expected 1-[1-amino-2-hydroxyethyl]-ferrocenes were isolated in poor yield together with other decomposition products.

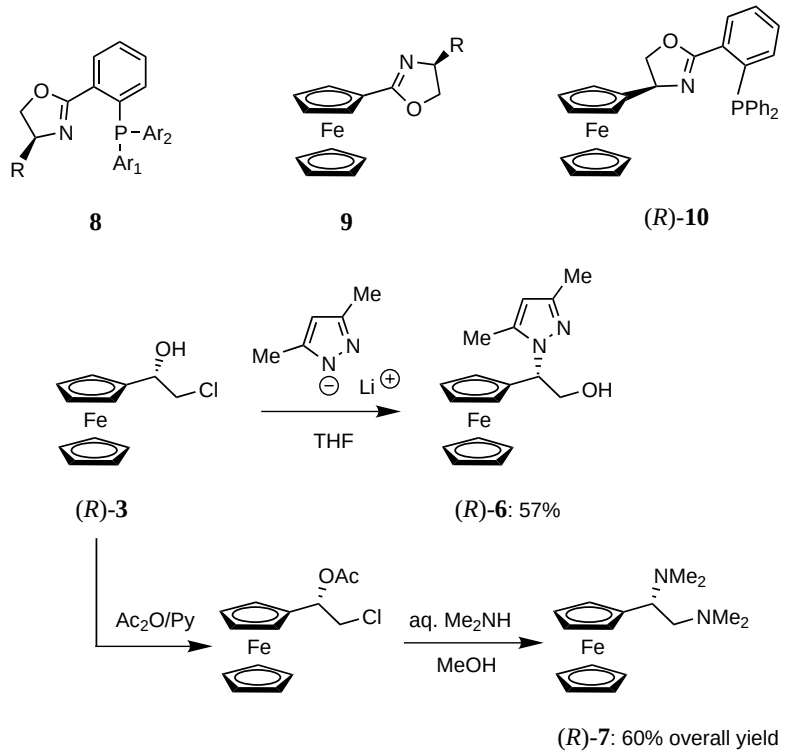
The pyrazole derivative (*R*)-**6** was prepared in 57% yield by reaction of (*R*)-**3** with lithiated 3,5-dimethylpyrazole, whereas double nucleophilic substitution of both groups in the side chain of (*R*)-**3** was obtained after its conversion into the acetoxy derivative which, on reaction with aq. Me_2NH, gave diamine (*R*)-**7** in satisfactory yield (Scheme 4).

2.2. Synthesis and catalytic activity of ferrocenylphosphinooxazoline (*R*)-10

Enantiomerically pure β-amino alcohols are important intermediates for the preparation of several ligands used in asymmetric catalysis.[10] Among their derivatives, oxazolines have attracted great interest due to their structural versatility and efficiency in hydrosylilation, allylic alkylation and cyclopropanation.[11] Independently Pfaltz and other groups have developed 2-(phosphinoaryl)-oxazolines **8** with additional potentially stereogenic phosphorous atom,[12] whereas ferrocenyloxazolines **9** have been mainly used as starting material for diastereoselective metalation on the cyclopentadienyl ring.[3b,13]



Scheme 3.

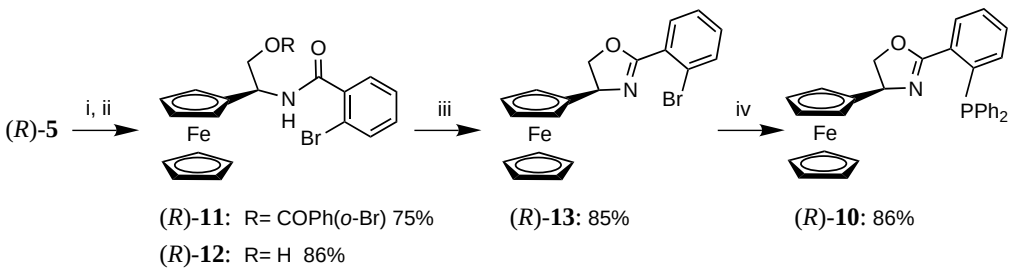


Scheme 4.

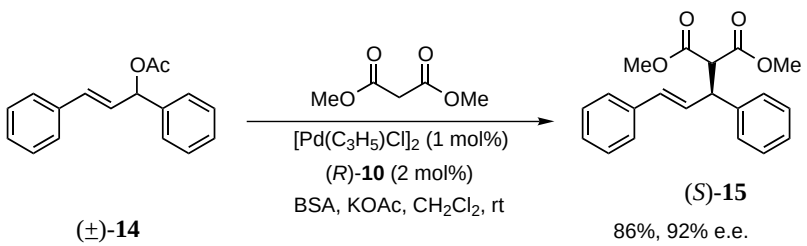
We have prepared ferrocenyloxazoline **10** from amino alcohol (*R*)-**5** following Scheme 5. In comparison to the one-pot Vorbruggen method this route consists of more steps[14] but allowed easy purification of the intermediate products and gave a better overall yield of (*R*)-**13** (55 versus 25%).

Treatment of (*R*)-**5** with 2-bromobenzoyl chloride (2.5 equiv.) gave amide-ester **11** (75% yield) which was selectively hydrolysed to the corresponding amide **12** (86% yield); tosylation of the free hydroxyl group of **12** and in situ ring closure with excess triethylamine gave oxazoline (*R*)-**13** (85% yield) whose bromine atom was replaced by a diphenylphosphino group after metalation with *n*-BuLi (1.1 equiv.) and subsequent reaction with chlorodiphenylphosphine to give (*R*)-**10** in 86% yield.

In order to evaluate the catalytic activity of (*R*)-**10**, this ligand was tested in the asymmetric allylic alkylation of (*E*)-1,3-diphenyl-2-propenyl acetate **14** (Scheme 6) using dimethyl malonate as nucleophile.[15]



Scheme 5. *Reagents and conditions*: (i) 2-Bromobenzoyl chloride (2.5 equiv.), TEA, dioxane, 0°C; (ii) K_2CO_3 in MeOH, rt; (iii) *p*-TsCl (2 equiv.), TEA (6 equiv.), CH_2Cl_2, reflux; (iv) *n*-BuLi (1.1 equiv.), THF, 78°C, $ClPPh_2$ (1.2 equiv.).



Scheme 6.

The alkylation reaction proceeded at room temperature in the presence of 2 mol% of the catalyst (prepared in situ from 1 mol% of $[Pd(C_3H_5)Cl]_2$ and 2 mol% of (*R*)-**10**, 2 equivalents of *N*,*O*-bis(trimethylsilyl)-acetamide and catalytic amounts of potassium acetate. After a reaction time of 4.5 h the alkylation product (*S*)-**15** could be isolated in 86% yield and 92% e.e.

3. Conclusion

In summary, using a short sequence we have prepared the new ferrocenyl phosphineoxazoline **10** which proved to be an efficient ligand for the palladium(0)-catalyzed allylic alkylation reaction. The applications of this chiral ligand in asymmetric catalysis are currently underway.

4. Experimental

4.1. General

All reactions were carried out under argon using standard Schlenk techniques. ^1H and ^{13}C NMR spectra were recorded on a Bruker AMX 250 or AC 300 instrument. Chemical shift (δ) are given as ppm relative to the residual solvent peak. Melting points are uncorrected. Fourier transformation IR spectra were recorded on a Nicolet 510 FTIR spectrometer. Optical rotations were measured on a DIP 135 JASCO instrument. Column chromatography was performed on silica gel 60 (70–230 mesh) using the specified eluants. Enantiomeric excess of substitution product **15** was determined by HPLC. A Chiracel OD column (Daicel Chemical Industries) was used with *n*-heptane/*iso*-propanol as a mobile phase and detection by a diode array UV–vis detector at 215 nm.

4.2. (*R*)-1-[1,2-Dihydroxyethyl]ferrocene, (−)-1a

Alcohol (−)-**3** (>98% e.e., 100 mg, 0.38 mmol) was dissolved in a dioxane/H_2O mixture (4:1, 5 mL) containing K_2CO_3 (75 mg). The solution was allowed to stand at room temperature overnight. After dilution with AcOEt and extraction with brine, the organic solution was taken to dryness and the residue purified on Si gel column (hexanes:AcOEt, 1:1) to give pure (−)-**1a** (96% e.e., 75 mg, 80% yield), $[\alpha]_D = -27.2$ ($c = 0.5$, EtOH, lit.[6] $[\alpha]_D = -23.3$ ($c = 0.1$, MeOH). Enantiomeric excess of (−)-**1** was determined by ^1H NMR in the presence of $Eu(hfc)_3$ after conversion into the corresponding diacetate.

4.3. (*R*)-1-[1-Amino-2-hydroxyethyl]ferrocene, (−)-5

Alcohol (−)-**3** (>98% e.e., 700 mg, 2.65 mmol) was dissolved in a dioxane/H_2O mixture (4:1, 30 mL) and 30% aq. NH_4OH (10 mL) was added. The reaction mixture was stirred for 4 h at 50°C and then left to stand overnight at room temperature. The solution was diluted with H_2O and extracted with AcOEt. The organic phase was partitioned with 10% citric acid solution and the organic layer discarded. After treatment with NaOH to give a pH of 11, the aqueous phase was extracted with AcOEt. This final organic phase was washed with brine, dried over Na_2SO_4 and concentrated to dryness to afford pure amino alcohol (−)-**5** as a gold-yellow solid (460 mg, 70% yield, >95% e.e.), mp 92–93°C, $[\alpha]_D = -11.0$ ($c = 0.52$, $CHCl_3$); IR (KBr): ν_{max} 3420 (s), 2954 (s), 1463 (m), 1037 (m), 814 (m); ^1H NMR (CD_3OD/D_2O): δ 3.56 (dd, 1H, $J = 9.5$ and 12.0 Hz), 3.83 (dd, 1H, $J = 4.0$ and 12.0 Hz), 3.83 (dd, 1H, $J = 4.0$ and 9.5 Hz) 4.23 (m, 3H), 4.25 (s, 5H), 4.30 (m, 1H); ^{13}C NMR (CD_3OD): δ 53.47, 67.08, 67.82, 68.34, 68.62, 68.73, 69.45, 90.91; MS (EI, 70 eV): m/z (%): 245 (M^+, 46), 214 (100), 199 (35), 186 (24), 121 (38). Anal. calcd for $C_{12}H_{15}FeNO$: C, 58.80; H, 6.17; N, 5.72; found: C, 58.56; H, 6.02; N, 5.61%.

The enantiomeric excess of (−)-**5** was determined by integration of diastereoisomeric methylenic proton resonances -CH_2SO_2R (double doublet, $J = 15$ Hz, AB system, δ 2.93 and 3.20 for one diastereomer and 3.06 and 3.69 for the other diastereomer) of the corresponding amide obtained by reaction with (1*S*)-camphorsulphonyl chloride.

4.4. Synthesis of (−)-5 from (−)-1a

Diol (−)-**1a** (50 mg, 0.20 mmol, 96% e.e.) was acetylated with Ac_2O/Py at room temperature overnight. After removal of the reagents under vacuum, the crude residue was dissolved in MeOH containing 30% aq. NH_4OH (1 mL) and the mixture was left to stand overnight at room temperature. The solution was diluted with H_2O, extracted with AcOEt and the organic phase partitioned with 10% citric acid solution. The organic layer contained compound **1a** as a consequence of the hydrolysis of the starting diester. After alkalinization with NaOH to pH 11, the aqueous phase was extracted with AcOEt. This final organic phase was washed with brine, dried over Na_2SO_4 and taken to dryness. The residue was purified on silica gel column (MeOH:CH_2Cl_2, 3:2) to give amino alcohol (−)-**5** (18 mg, 0.07 mmol, 35% yield), $[\alpha]_D = -10.8$ ($c = 0.35$, $CHCl_3$).

4.5. (*R*)-1-[1-(3,5-Dimethylpyrazolyl)-2-hydroxyethyl]-ferrocene, (−)-6

A solution of 3,5-dimethylpyrazole (41 mg, 0.42 mmol) in THF (2 mL) was treated with *n*-BuLi (15% solution in hexane, 0.20 mL) at −78°C. The temperature was then raised to −40°C and the solution was added dropwise to a flask containing a solution of alcohol (−)-3 (>98% e.e., 100 mg, 0.38 mmol) dry THF (5 mL). The reaction mixture was maintained at −40°C for 1 h, then warmed to room temperature and allowed to stand overnight. After dilution with AcOEt and extraction with brine, the organic solution was taken to dryness and the residue purified on silica gel column (*n*-pentane:diethyl ether, 2:3) to give pure (−)-**6** (70 mg, 57% yield), mp 121–122°C, $[\alpha]_D = -28.5$ ($c = 0.42$, $CHCl_3$); IR (KBr): ν_{max} 3428 (s), 3276 (s), 1636 (m), 1555 (s),

1046 (s), 807 (s); ^{1}H NMR ($CDCl_3$): δ 2.21 (s, 3H), 2.29 (s, 3H), 4.10 (s, 5H), 4.13 (bs, 2H), 4.18 (m, 1H), 4.22 (bs, 1H), 4.25 (bs, 1H), 4.38 (dd, 1H, J=7.4 and 11.4 Hz), 5.01 (dd, 1H, J=4.0 and 7.4 Hz), 5.79 (s, 1H); ^{13}C NMR ($CDCl_3$): 11.74, 14.04, 58.60, 65.65, 67.95, 68.08, 68.20, 68.33, 69.14, 86.72, 105.33, 139.66, 148.02; MS (EI, 70 eV): m/z (%): 324 (M^+, 100), 293 (38), 228 (27), 163 (37), 121 (22). Anal. calcd for $C_{17}H_{20}FeN_2O$: C, 62.98; H, 6.22; N, 8.64; found: C, 62.48; H, 6.11; N, 8.42%.

4.6. (*R*)-1-[1,2-(Dimethylamino)ethyl]ferrocene, (+)-7

Alcohol (−)-**3** was converted into the corresponding acetate by conventional acetylation (Ac_2O/Py); after removal of the reagents under vacuum the crude residue was used without further purification. Acetate (100 mg, 0.33 mmol) was dissolved in MeOH (5 mL) and an aq. $NH(CH_3)_2$ solution of (33% 2 mL) was added. The solution was left overnight at room temperature, then diluted with water and extracted with AcOEt. The organic phase was partitioned with a 10% citric acid solution and the organic layer discarded. After alkalinization with NaOH to pH 11, the aqueous phase was extracted with AcOEt. This final organic phase was washed with brine, dried over Na_2SO_4 and taken to dryness affording a residue that was purified by preparative TLC (silica gel, n-BuOH:HOAc:H_2O, 60:15:25, R_f 0.45) to give diamine **7** as acetate salt. Free (+)-**7** was obtained after alkalinization with NaOH and extraction with CH_2Cl_2 (59 mg, 60%) as a yellow solid, 122°C decomposed; $[\alpha]_D$=+47.6 (c=0.25, $CHCl_3$); IR (KBr): ν_{max} 3075 (w), 2922 (s), 1461 (m), 1261 (m), 1028 (m), 810 (m); ^{1}H NMR (CD_3OD): δ 2.03 (s, 6H), 2.41 (s, 6H), 2.85 (dd, 1H, J=4.2 and 13.0 Hz), 2.93 (dd, 1H, J=10.0 and 13.0 Hz), 3.70 (dd, 1H, J=4.2 and 10.0 Hz), 4.06 (m, 1H), 4.17 (s, 5H), 4.20 (m, 3H); ^{13}C NMR (CD_3OD): δ 40.78, 46.12, 60.96, 62.20, 68.16, 68.34, 68.74, 69.75, 70.69, 83.44. MS (EI, 70 eV) m/z (%): 300 (9), 255 (14), 242 (100), 227 (93), 121 (86), 58 (75). Anal. calcd for $C_{16}H_{24}FeN_2$: C, 64.01; H, 8.06; N, 9.33; found: C, 64.37; H, 8.26; N, 9.45%.

4.7. (*R*)-*N*-(1-Ferrocenyl-2-hydroxyethyl)(2-bromophenyl)carboxamide, (−)-12

Amino alcohol (−)-**5** (>95% e.e., 500 mg, 2.04 mmol) was dissolved in dry dioxane (10 mL) containing triethylamine (1.14 mL, 8.2 mmol). To this mixture a solution of 2-bromobenzoyl chloride (0.67 mL, 5.10 mmol) in 5 mL of dioxane was added dropwise during 20 min at 0°C and a white precipitate formed. After stirring at room temperature for an additional 1 h the solvent was removed under vacuum and the residue suspended in diethyl ether. The precipitate was removed by filtration and the solution concentrated to dryness. The residue was purified by column chromatography (silica gel, hexanes:ethyl acetate from 9:1 to 3:2) to give **11** (935 mg, 75% yield): ^{1}H NMR ($CDCl_3$): δ 4.22 (m, 2H), 4.24 (s, 5H), 4.31 (m, 1H), 4.34 (m, 1H), 4.71 (dd, 1H, J=6.3 and 11.3 Hz), 4.79 (dd, 1H, J=4.3 and 11.3 Hz), 5.57 (ddd, 1H, J=4.3, 6.3 and 9.0 Hz), 6.45 (d, 1H, J=9.0 Hz, -NH), 7.26–7.43 (m, 4H), 7.55 (dd, 1H, J=1.8 and 7.5 Hz), 7.61 (dd, 1H, J=1.5 and 8.0 Hz) 7.68 (m, 1H), 7.90 (m, 1H); ^{13}C NMR ($CDCl_3$): δ 47.90, 66.60, 67.22, 68.13, 68.87, 85.73, 119.14, 121.78, 127.29, 127.62, 129.51, 131.38, 131.80, 132.82, 133.46, 134.36, 137.54, 165.85, 166.76. Anal. calcd for $C_{26}H_{21}Br_2FeNO_3$: C, 51.10; H, 3.46; N, 2.29; found: C, 50.82; H, 3.38; N, 2.26%.

Compound **11** (935 mg, 1.53 mmol) was dissolved in MeOH (20 mL) containing K_2CO_3 (0.2 g) and the suspension stirred at room temperature for 2 h. After dilution with H_2O the solution was extracted with AcOEt and the organic phase dried over Na_2SO_4 and taken to dryness. The residue was purified by column chromatography (silica gel, hexanes:AcOEt, 3:2) to give amide (−)-**12** (562 mg, 86% yield) as a yellow solid, mp 109°C; $[\alpha]_D$=−36.5 (c=0.76, $CHCl_3$); IR (KBr): ν_{max} 3555 (m), 3458 (m), 3280 (m), 1636 (s), 1537 (m), 1030 (m), 811 (m); ^{1}H NMR ($CDCl_3$): δ 3.91 (dd, 1H, J=5.5 and 11.0 Hz), 4.06 (dd, 1H, J=2.5 and 11.0 Hz), 4.22 (bs, 7H), 4.27 (m, 2H), 5.14 (m, 1H), 6.59 (d, 1H, J=7.2 Hz), 7.32 (dt, 1H, J=1.8 and 7.5 Hz), 7.41 (dt, 1H, J=1.3 and 7.5 Hz), 7.62 (dd, 1H, J=1.8 and 7.5 Hz), 7.65 (dd, 1H, J=1.3 and 7.5); ^{13}C NMR ($CDCl_3$): δ 51.67, 66.66, 66.80, 68.18, 68.84, 86.19, 119.13, 127.68, 129.63, 131.48, 133.46, 137.42, 167.65. MS (EI, 70 eV) m/z (%): 429 [(M+2)$^+$, 28], 427 (M^+, 29), 411 (92), 409 (94), 346 (31), 344 (33), 264 (41), 199 (31), 183 (69), 121 (100), 105 (57), 91 (65), 77 (58). Anal. calcd for $C_{19}H_{18}BrFeNO_2$: C, 53.31; H, 4.24; N, 3.27; found: C, 53.58; H, 4.19; N, 3.39%.

4.8. (*R*)-4-Ferrocenyl-2-(2-bromophenyl)-1,3-oxazoline, (+)-13

Amide (−)-**12** (320 mg, 0.75 mmol) was dissolved in CH_2Cl_2 (10 mL) and triethylamine (0.62 mL, 4.46 mmol) and p-TsCl (0.30 g, 1.57 mmol) were added. The solution was heated under reflux for 24 h then extracted with water and the organic phase washed with brine, dried over Na_2SO_4 and concentrated to dryness. The residue was chromatographed on silica gel column (hexanes:AcOEt, 9:1) to give pure (+)-**13** (260 mg, 0.64 mmol, 85% yield), mp 89–90°C, $[\alpha]_D$=+54.1 (c=0.50, $CHCl_3$); IR (KBr): ν_{max} 3045 (w), 2362 (m), 1632 (s), 1101 (m), 1025 (s), 825 (m), 737 (m); ^{1}H NMR ($CDCl_3$): δ 4.22 (bs, 8H), 4.33 (m, 1H), 4.55 (t, 1H, J=8.0 Hz), 4.75 (dd, 1H, J=8.0 and 10.0 Hz), 5.19 (dd, 1H, J=8.0 and 10.0 Hz), 7.32 (dt, 1H, J=2.0 and 7.5 Hz), 7.39 (dt, 1H, J=1.5 and 7.5 Hz), 7.69 (dd, 1H, J=1.5 and 7.5 Hz), 7.78 (dd, 1H, J=2.0 and 7.5 Hz); ^{13}C NMR ($CDCl_3$): δ 65.76, 66.43, 67.01, 67.92, 68.08, 68.47, 73.69, 89.90, 121.84, 127.05, 129.67, 131.45, 131.63, 133.84, 162.86. MS (EI, 70 eV) m/z (%):411 [(M+2)$^+$, 95], 409 (M^+, 100), 329 (18), 264 (52), 222 (34), 199 (19), 182 (18), 121 (78), 77 (52). Anal. calcd for $C_{19}H_{16}BrFeNO$: C, 55.65; H, 3.93; N, 3.41; found: C, 55.36; H, 3.87; N, 3.35%.

4.9. (*R*)-4-Ferrocenyl-2-[(2-diphenylphosphino)phenyl]-1,3-oxazoline, (+)-10

To a solution of oxazoline (+)-**13** (288 mg, 0.70 mmol) in THF (5 mL) under argon was added dropwise n-BuLi (0.53 mL of 15% in hexane) at −78°C. After stirring the mixture at the same temperature for 1 h

chlorodiphenylphosphine (0.15 mL, 0.84 mmol) was slowly added and the cooling bath was removed. The solution was stirred for 45 min at room temperature, quenched with saturated NH_4Cl solution (10 mL) and extracted with diethyl ether. After drying over $MgSO_4$ and filtration, the residue was purified by column chromatography (*n*-pentane/diethyl ether, 6:1). (*R*)-**10** was isolated as an orange solid (310 mg, 0.6 mmol, 86%), mp 72°C, $[\alpha]_D = +72.5$ ($c = 1.04$, $CHCl_3$); IR (KBr): ν_{max} 3050 (w), 1648 (s), 1433 (m), 1030 (m), 743 (s), 696 (s), 484 (m); ^{1}H NMR ($CDCl_3$): δ 3.86–3.87 (m, 1H), 3.99–4.01 (m, 1H), 4.05–4.10 (m, 7H), 4.25 (t, 1H, $J = 8.1$ Hz), 4.41 (dd, 1H, $J = 9.9$ Hz and 8.1 Hz), 4.94 (dd, 1H, $J = 9.9$ Hz and 8.1 Hz), 6.92–6.96 (m, 1H), 7.41–7.29 (m, 12H), 7.97–8.02 (m, 1H); ^{13}C NMR ($CDCl_3$): δ 65.45, 66.53 (d, $J = 1.2$ Hz), 66.85, 67.56, 67.86, 68.37, 73.08, 90.16, 128.08, 128.32–128.51 (m), 129.96, 130.01, 130.49, 131.78, 132.04, 133.66, 133.95 (d, $J = 1.9$ Hz), 134.03, 134.24, 138.17, 138.20, 138.33, 138.66, 139.00, 163.24 (d, $J = 2.3$ Hz); ^{31}P NMR ($CDCl_3$): δ 4.85; MS (EI, 70 eV) m/z (%): 515 (M^+, 2), 450 (2), 424 (10), 331 (3), 213 (15), 212 (100), 183 (4), 121 (8), 106 (54), 105 (23), 91 (89); HRMS calcd for $C_{31}H_{26}FeNOP$: 515.1101. Observed: 515.1147.

4.10. Pd-catalysed allylic substitution

In a 25 mL Schlenk tube under argon (*R*)-**10** (6.6 mg, 0.0128 mmol) and allylpalladium chloride dimer (2.3 mg, 0.0064 mmol) were dissolved in CH_2Cl_2 (5 mL). 3-Acetoxy-1,3-diphenylpropene (168 mg, 0.64 mmol), BSA (0.31 mL, 1.28 mmol, 2 equiv.), dimethyl malonate (0.14 mL, 1.28 mmol, 2 equiv.) and potassium acetate (3.2 mg, 0.03 mmol) were added and the solution was stirred at room temperature for 4.5 h. After addition of saturated aqueous NH_4Cl solution, the mixture was extracted with diethyl ether. The organic layer was washed with brine, dried over $MgSO_4$ and concentrated. The crude product was purified by column chromatography (*n*-pentane/diethyl ether, 5:1). Compound **15** was isolated as a colorless oil (179 mg, 0.55 mmol, 86% yield, 92% e.e.). Enantiomeric excess was determined by HPLC (OD, 97% *n*-heptane/3% *iso*-propanol, 0.4 mL/min): t_R (min) = 32.15 (*R*), 34.55 (*S*). $[\alpha]_D = -17.3$ ($c = 1.35$, EtOH). The absolute configuration of **15** was assigned by comparison of the optical rotation value with literature data.[16]

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