A Straightforward Asymmetric Synthesis of Enantiopure 1,2-Disubstituted Ferrocenes

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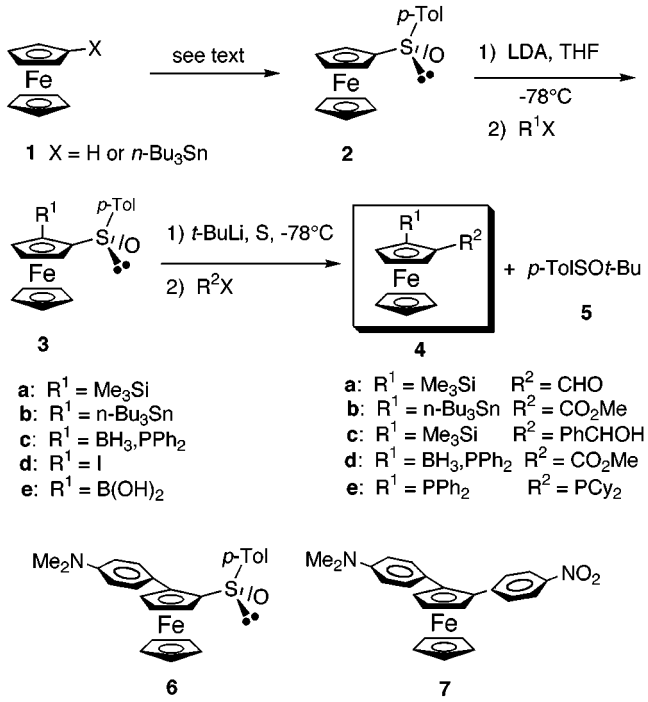
New methods for the practical asymmetric synthesis of 1,2-disubstituted ferrocene derivatives have recently received much attention.[1] The main method which has been used since the early 1970s for the preparation of enantiopure ferrocenes relied on a diastereoselective lithiation of (*N*,*N*-dimethylamino)methyl ferrocene (Ugi's amine).[2] From this pioneering work, hundreds of chiral ferrocenyl ligands have been synthesized and used in asymmetric catalysis.[3] In the search for new methodologies without a resolution step, practical diastereoselective, as well as enantioselective, methods have been recently achieved. Thus, ferrocenyl complexes bearing temporary chiral functionalities such as acetals,[4] oxazolines,[5] or a chiral amine[6] have been reported to give high diastereoselectivities in ortholithiation−electrophilic quenching sequences. The acetal method gave a general access to enantiopure ortho-substituted ferrocenecarboxaldehydes. In the case of the oxazolines, removal of the chiral auxiliary group involved a multireaction sequence,[5b] although it was shown that the oxazoline group itself could be useful in the chelating structure of some new chiral ligands.[1,5c] A second process relies on an enantioselective ortholithiation of a ferrocenyl complex bearing an achiral ortho-directing agent.[7−9] The reagent can be either a chiral lithium amide or an alkyllithium/chiral ligand (such as sparteine) combination. A major limitation of all the previous methods is that the ortho-directing group of the substrate seldom allows functional group modification. Thus, there has been so far no method for the stepwise enantioselective introduction of various vicinal groups on the ferrocene ring.

Scheme 1



We wish to report a strategy based on a chiral ferrocenyl sulfoxide. This approach is described in Scheme 1 and is a three-step process starting from ferrocene **1**. The first step is the preparation of (*R*)- or (*S*)-ferrocenyl *p*-tolyl sulfoxide **2** from ferrocene. This reaction has been previously investigated by us[10] using (tri-*n*-butylstannyl)ferrocene (easily transformed into ferrocenyllithium by *n*-BuLi) and commercially available (R_S)- or (S_S)-menthyl *p*-tolyl sulfinate (72% yield, >99.8% ee). We also discovered that the direct lithiation of ferrocene according to the procedure of Mueller−Wersterhoff[11] followed by inverse addition of the lithio derivative on menthyl *p*-toluenesulfinate gave sulfoxide **2** in 69% yield and 83% ee (99.3% ee after recrystallization in 47% yield, see Experimental Section for details). This is a practical alternative for the multigram synthesis of (*R*)- and (*S*)-**2**.[12]

The second step of the process is the highly diastereoselective ortho-functionalization of sulfoxide **2** into sulfoxide **3**. We previously established that ortholithiation by LDA at −78 °C in THF followed by electrophilic quenching by TMSCl or *n*-Bu_3SnCl is highly diastereoselective (98%),[13] giving rise to **3a** or **3b**, respectively, in excellent yield.[14] The relative stereochemistry has been assigned by analogy with similar reactions on *tert*-butyl ferrocenyl sulfoxide.[13] We extended the electrophilic quenching to a wide range of electrophilic reagents,

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(1) Review: (a) Togni, A. *Angew. Chem.* **1996**, *108*, 1581; *Angew. Chem Int. Ed. Engl.* **1996**, *35*, 1475. (b) Kagan, H. B.; Riant, O. *Advances in Asymmetric Synthesis*; Hassner, A., Ed.; JAI Press Inc.: Greenwich, CT, 1997; Vol. 2, pp 189−235.

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(9) Nishibayashi, Y.; Arikawa, Y.; Ohe, K.; Uemura *J. Org. Chem.* **1996**, *61*, 1172.

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(11) Sander, R.; Mueller-Westerhoff, U. T. *J. Organomet. Chem.* **1996**, *512*, 219.

(12) The procedure in ref 10 has the advantage to avoid in situ racemization of **2** promoted by a slight excess of lithioferrocene, as already found,[10,13] and also recently noticed by Hua et al.[18]

(13) Rebiere, F.; Riant, O.; Ricard, L.; Kagan, H. B. *Angew. Chem., Int. Ed. Engl.* **1993**, *32*, 568.

(14) Absolute configuration of planar chirality was named according to the Schlögl nomenclature: Schlögl, K. *Topics Stereochem.* **1967**, *1*, 39.

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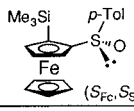
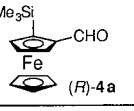
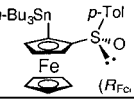
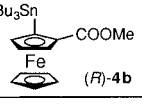
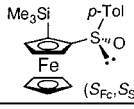
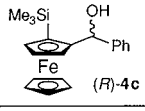
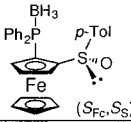
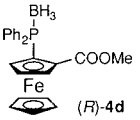
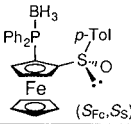
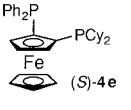
Table 1. Products and Yields of the Substitution of Ferrocenyl Sulfoxides 3a−c

Entry	Starting sulfoxide[a]	Electrophile	Product	Yield (%)
1	 (S_{Fc},S_S)-**3a**	Me_3SiCl	 (*R*)-**4a**	88[b,d] 88[c,d]
2	 (R_{Fc},S_S)-**3b**	$ClCO_2Me$	 (*R*)-**4b**	90[b,e]
3	 (S_{Fc},S_S)-**3a**	PhCHO	 (*R*)-**4c**	80[b,f]
4	 (S_{Fc},S_S)-**3c**	$ClCO_2Me$	 (*R*)-**4d**	64[b,g]
5	 (S_{Fc},S_S)-**3c**	$ClPCy_2$	 (*S*)-**4e**	19[b,h]

[a] For the synthesis of the starting sulfoxides **3a**−**c** and products **4a**−**4e**: see Experimental Section. [b] Reaction performed in diethyl ether. [c] Reaction performed in THF. [d] ee > 99.5% by chiral HPLC. [e] ee > 95% by polarimetry after conversion to the known aldehyde.[24a,b] [f] The two diastereomers (1/1 ratio) were separated by chromatography on silica gel. [g] 25% of the starting sulfoxide **3c** was recovered. 99% ee measured by chiral HPLC after removal of BH_3. [h] Overall yield after removal of the borane protecting group. 43% of the starting sulfoxide **3c** was recovered (57% conversion).

yielding the sulfoxides **3a**−**e** in good to excellent yields and high diastereoselectivity (98%).[15] Clearly, this methodology allows the introduction of a wide range of R^1 substituents. The last step of our method is the introduction of the R^2 group, by replacement of the sulfoxide moiety. For this purpose, we took advantage of the well-known substitution reaction of alkyllithiums on aryl sulfoxides, with formation of dialkyl sulfoxides (almost racemized).[16] This reaction simultaneously generates in situ an aryllithium, usually destroyed during workup. We found that *tert*-BuLi in diethyl ether or THF at −78 °C gave attack cleanly at sulfur with formation of racemic sulfoxide **5** and a chiral lithioferrocene **4** (R^2 = Li) which may be trapped by various electrophiles (such as PhCHO, ClCOOMe, $ClPCy_2$, DMF) to give the corresponding chiral ferrocenes **4**. The chemical yields for the transformation **3** → **4** is good to excellent, with full stereochemical control on the final ferrocene. For example, chiral HPLC showed ee > 99.5% in the case of **4a** and **4e**.

It is interesting to note that diphosphine **4e** is an unprecedented type of chiral 1,2-diphosphine where the planar chirality relies only on the difference of groups at the two phosphorus atoms. We are currently generalizing this approach to the synthesis of analogues of **4e**, as well as their evaluation in asymmetric catalysis.[19]

This new method could also be extended to the creation of carbon−carbon bond on the cyclopentadienyl rings. Thus, ortho-lithiation of sulfoxide (*S*)-**2** with LDA in THF followed by transmetalation with zinc chloride and coupling with *p*-(dimethylamino)iodobenzene using a Pd catalyst ($Pd_2(dba)_3$/2 $Pfur_3$)[20] gave α-aryl sulfoxide (S_{Fc},S_S)-**6** in 37% yield. Sulfoxide (S_{Fc},S_S)-**6** was transmetalated with *tert*-BuLi followed by $ZnCl_2$ and then reacted with *p*-nitroiodobenzene and a Pd° catalyst to yield enantiopure 1,2-biarylferrocene (*S*)-**7** (61% yield, unoptimized).

In conclusion, we have devised a useful method for preparing enantiopure 1,2-disubstituted ferrocenes of a predictable absolute configuration. It allows the construction of a wide range of substituted ferrocenes with application as new chiral ligands (e.g. diphosphine **4e**) or new molecular structures (e.g. donor−acceptor system **7**). Moreover, this approach should also lead to the easy synthesis of diverse types of 1,2-disubstituted ferrocenes (achiral, racemic, or enantiopure). We are currently investigating the scope of this reaction.

Experimental Section

Optical rotations were measured at 589 nm on a Perkin Elmer 241 polarimeter. Concentrations (*c*) are reported in g/100 mL. In the case of highly colored complexes, a cell of 1 cm length was used to avoid strong absorbtion of the light by the solution in order to obtain reproducible results. Elemental analyses were performed by the "Service de microanalyse du CNRS" at Gif sur Yvette. All reactions requiring anaerobic and anhydrous conditions were conducted under Ar in oven-dried glassware. *tert*-Butyllithium was purchased from Acros as a 1.5 M solution in pentane and was regularly titrated using *N*-pivaloyltoluidine. "Standard workup" refers to extraction of the reaction mixture with an organic solvent, washing of the extract with water and brine, drying over anhydrous magnesium sulfate, and removal of the solvents under reduced pressure on a rotary evaporator. Analytical HPLC were recorded on a HPLC machine equipped with a Spectra Series P100 pump and a Spectra Series UV100 detector. The chiral stationary phase was a Daicel Chiralcel OD-H column. The absolute configuration of the planar chirality of ferrocenes was given with the nomenclature of Schlögl.[14] Preparation of sulfoxides **3d** and **3e**: see ref 21.

(*S*)-Ferrocenyl *p*-Tolyl Sulfoxide (2). Method A. The sulfoxide was prepared from tris-*n*-butyl stannyl ferrocene on a 50 mmol scale by the procedure described.[10] Enantiomerically pure (*S*)-**2** was isolated in a 72% yield. The conditions used for the chiral HPLC analysis of the ee of **2** were hexane-*i*-PrOH 90/10, flow rate 0.5 mL/min, λ = 254 nm (*R*)-**2** 23.5 min, (*S*)-**2** 27.3 min.

Method B. A dry Schlenk tube was charged with 14.9 g (80 mmol, 2 equiv) of ferrocene, 450 mg of *t*-BuOK (4 mmol, 0.1 equiv), and 200 mL of freshly distilled THF under Ar. After cooling the suspension to −78 °C, 25.5 mL of a 1.5 M solution of *tert*-BuLi (38 mmol, 0.95 equiv) was added dropwise via canula, and the mixture was stirred for 30 min. The cooling

(15) Full details of the accurate measurement of the diastereoselectivity of the lithiation of **2** will be reported elsewhere.

(16) Addition of alkyllithium at sulfur of some aryl sulfoxides with departure of an aryllithium and formation of an alkyl sulfoxide is not unprecedented. (a) Jacobus, J., Mislow, K. *J. Am. Chem. Soc.* **1967**, *89*, 5228. (b) Lockard, J. P.; Schroeck, C. W.; Johnson, C. R. *Synthesis* **1973**, 485. (c) Durst, T.; LeBelle, M. J.; Van den Elzen, R.; Tin, K.-C. *Can. J. Chem.* **1974**, *52*, 761.). It has been also observed for alkynyl and vinyl sulfoxides,[17] as well as for *p*-tolyl ferrocenyl sulfoxide.[18]

(17) Zhao, S. H.; Samuel, O.; Kagan, H. B. *Tetrahedron* **1987**, *43*, 5135.

(18) Hua, H. D.; Lagneau, N. M.; Chen, Y.; Robber, P. M.; Clapham, G.; Robinson, P. D. *J. Org. Chem.* **1996**, *61*, 4508.

(19) These compounds could hardly be prepared by any other existing approaches, apart from enantioselective deprotonation of ferrocenyl diphenylphosphine oxide (which gave moderate enantioselectivities. See ref 7.

(20) Rottländer, M.; Palmer, N.; Knochel, P. *Synlett* **1996**, 573.

(21) Guillaneux, D., Ph.D. thesis, Orsay, 1995. Paper in preparation.

batch was removed, and the suspension was stirred at rt for another 30 min before cooling to −25 °C with a CCl_4/dry ice bath. The suspension of lithioferrocene was slowly transferred (in about 30 min) via a canula to a cooled (25 °C) solution of 11.8 g of (−)-(1*R*)-menthyl (S_S)-toluene-4-sulfinate (40 mmol, 1 equiv) in 100 mL of dry THF, and stirring was maintained for a further 15 min before quenching at the same temperature with 40 mL of water. The reaction mixture was extracted with ether, and the organic phase was washed with brine and water. After standard workup, 26 g of an orange solid was obtained and chromatographed on 200 g of silica gel (hexane/ether 50/50 to remove ferrocene and menthol, and then ether /CH_2Cl_2 4/1 to elute the sulfoxide. A 9 g amount of crystalline yellow (*S*)-**2** was recovered (69%, 83% ee). One crystallization from ether (50 mL), CH_2Cl_2 (20 mL), and hexane (20 mL) (24 h at −25 °C) gave 6.7 g of crystals (96.2% ee). A second crystallization (30 mL of ether + 5 mL of CH_2Cl_2 + 20 mL of hexane) gave 6 g of sulfoxide **2** (47% yield, 99.3% ee).

General Procedure for the Asymmetric Deprotonation of Sulfoxide (*S*)-2: (S_{Fc},S_S)-*p*-Tolylsulfinyl)-2-(trimethylsilyl)ferrocene (3a). To a stirred suspension of sulfoxide (*S*)-**2** (1.6 g, 5 mmol) in 30 mL of dry THF at −78 °C under Ar was added 2.75 mL of a 2 M solution of LDA (5.5 mmol) dropwise via a syringe. The sulfoxide dissolved during the addition, and the resulting red-orange solution was stirred at −78 °C for 20 min before addition of 650 μL of Me_3SiCl (5 mmol). After stirring at the same temperature for 1 h, the light brown solution was quenched with 10 mL of a 1 N NaOH solution and worked up as usual. The crude reaction mixture was purified by FC on silica gel (hexane/ether: 70/30). A 1.75 g amount of pure sulfoxide (S_{Fc},S_S)-**3a** was isolated as a red solid (88%) along with 80 mg of recovered starting material (*S*)-**2** (4.9%) and 16 mg (0.8%) of the minor diastereoisomer (R_{Fc},S_S)-**3a**; mp 83−84 °C; $[\alpha]^{20}_D = -348$ ($c = 0.51$, $CHCl_3$); ^{1}H NMR δ 0.38 (9H, s), 2.43 (3H, s), 3.92 (1H, m), 4.14 (5H, s), 4.31 (1H, m), 4.37 (1H, m), 7.33 (2H, d), 7.68 (2H, d). ^{13}C NMR δ 0.3, 21.3, 69.5, 70.7, 71.6, 74.6, 77.2, 98.5, 125.2, 129.1, 140.1, 141.1; MS (EI) *m*/*e* 396 (M, 34%), 380, (100%, M − O). Anal. Calcd for $C_{20}H_{24}FeOSSi$: C, 60.59; H, 6.11; S, 8.09. Found: C, 60.57; H, 6.21; S, 8.05.

(R_{Fc},S_S)-(*p*-Tolylsulfinyl)-2-(tri-*n*-butylstannyl)ferrocene (3b). According to the general procedure, 1.6 g of sulfoxide (*S*)-**2** was reacted with LDA (1.1 equiv) and 1.63 mL of Bu_3SnCl (6 mmol). The reaction time with the electrophile was 90 min at −78 °C and 90 min at rt. Sulfoxide (R_{Fc},S_S)-**3b** was isolated as a red oil after FC on silica gel (hexane/ether 70/30) in a 88% yield. $[\alpha]^{20}_D = -51$ ($c = 0.25$, $CHCl_3$); ^{1}H NMR δ 0.85−0.93 (9H, m), 1.04−1.16 (6H, m), 1.24−1.42 (6H, m), 1.45−1.60 (6H, m), 2.38 (3H, s), 4.19 (5H, m), 4.23 (2H, m), 4.44 (1H, m), 7.25 (2H, d), 7.53 (2H, d); ^{13}C NMR δ 11.3, 13.7, 21.3, 27.4, 29.2, 69.5, 69.7, 69.8, 72.4, 77.0, 77.3, 124.9, 129.2, 140.7, 142.1; MS (CI) 631 (13%, M + NH_4^+), 614 (5%, M + H^+), 557 (100%, M − *n*-Bu + H^+). Anal. Calcd for $C_{29}H_{42}$-FeOSSn: C, 56.80; H, 6.91; S, 5.23. Found: C, 56.85; H, 7.11; S, 5.12.

(S_{Fc},S_S)-(*p*-Tolylsulfinyl)-2-[diphenylphosphino(borane)]-ferrocene (3c). According to the general procedure, 485 mg of sulfoxide (*S*)-**2** (1.5 mmol) was reacted with LDA (1.1 equiv) and 360 μL of Ph_2PCl (2 mmol). After stirring at −78 °C for 1 h, 4 mL of a 1 M solution of BH_3/THF was injected, and the solution was stirred at rt for 90 min before quenching and standard workup. Purification by FC on silica gel (ether) gave 450 mg of sulfoxide (S_{Fc},S_S)-**3c** as a crystalline yellow solid (57% yield) along with 150 mg of recovered (*S*)-**2** (0.46 mmol, 69% conversion); mp 112−114 °C; $[\alpha]^{20}_D = -410$ ($c = 0.16$, $CHCl_3$); ^{1}H NMR δ 1.0−1.7 (3H, m), 2.43 (3H, s), 4.11 (5H, s), 4.37 (1H, m), 4.51 (1H, m), 4.47 (1H, m), 7.10 (2H, m), 7.41−7.54 (6H, m), 7.65−7.85 (4H, m); ^{13}C NMR δ 21.5, 71.7, 71.0, 72.1, 72.4, 72.6, 73.3, 76.7 (d, $^2J_{P-C} = 12$ Hz), 99.0 (d, $^2J_{P-C} = 30$ Hz), 128.4, 128.5, 128.6, 129.3, 131.4 (d, $J_{P-C} = 19$ Hz), 133.2, 133.4, 133.6, 133.8, 140.6, 141.8; ^{31}P NMR δ 17.27 (1P, m); MS (CI) *m*/*e* 523 (91%, M + H^+), 509 (97%, M + H^+ − BH_3), 493 (97%, M + H^+ − BH_3 − O). Anal. Calcd for $C_{29}H_{28}FeBOPS$: C, 66.70; H, 5.41; S, 6.14; P, 5.93. Found: C, 66.14; H, 5.47; S, 5.91, P, 6.29.

(S_{Fc},S_S)-(*p*-Tolylsulfinyl)-2-[*p*-(dimethylamino)phenyl]-ferrocene (6). According to the general procedure, 485 mg of sulfoxide (*S*)-**2** (1.5 mmol) was reacted with LDA (1.1 equiv) for 20 min at −78 °C in 6 mL of dry THF. A 3 mL volume of a 0.5 M solution of $ZnCl_2$ in THF was injected dropwise, and the orange solution was stirred at −78 °C for 30 min. A solution 555 mg of *p*-(dimethylamino)iodobenzene (2.25 mmol) in 2 mL of THF was canulated followed by a preformed catalytic solution prepared from 27 mg of $Pd_2(dba)_3$/$CHCl_3$ (60 μmol, 4% Pd) and 28 g of trifurylphosphine (0.12 mmol, 8%) in 2 mL of THF. After stirring at rt overnight, the solution was refluxed for 6 h before quenching and workup. FC on silica gel (cyclohexane/EtOAc/CH_2Cl_2 60/30/10) followed by crystallization from ether/pentane afforded the orange crystalline sulfoxide **6** (247 mg) in a 37% yield: $[\alpha]^{20}_D = +50$ ($c =$ 0.2, chloroform); ^{1}H NMR δ 2.42 (3H, s), 2.97 (6H, s), 3.96 (1H, m), 4.07 (5H, s), 4.33 (1H, m), 4.63 (1H, m), 6.72 and 7.66 (4H, dd AB $J = 8.8$ Hz), 7.31 and 7.74 (4H, dd AB $J = 8$ Hz); ^{13}C NMR δ 21.5, 40.5, 68.4; 68.9, 70.9, 71.6, 97.0, 91.5, 112.1, 123.0, 125.8, 129.2, 130.4, 140.1, 141.3, 149.7. HRMS (EI) calcd for $C_{25}H_{25}SFeNO$ 443.1006, found 443.10066.

General Procedure for the Reaction of *tert*-Butyllithium on the Ferrocenyl Sulfoxides. (*R*)-2-(Trimethylsilyl)ferrocenecarboxaldehyde (4a). Procedure A in THF. To a 0.2 M solution of sulfoxide (S_{Fc},S_S)-**3a** (396 mg, 1 mmol) in freshly distilled THF at −78 °C under Ar was added 750 μL of a 1.5 M solution of *tert*-BuLi (1.1 equiv) dropwise (3 min) via a microsyringe. Upon addition of the *tert*-BuLi, a red color developed, and the solution was stirred for 5 min before injecting 230 μL of dry DMF. The solution was stirred at −78 °C for 2 h before quenching at the same temperature and standard workup. FC on silica gel (hexane/ether 70/30) delivered the aldehyde (*R*)-**4a** as a red solid (250 mg, 88% yield). Chiral HPLC on a OD-H column (λ = 254 nm, hexane/i-PrOH, 99/1 0.5 mL/min (*R*)-**4a** 12.7 min (*S*)-**4a** 14.5 min) showed ee ≥ 99.8% for the aldehyde; $[\alpha]^{20}_D = +205$ ($c = 0.73$, EtOH) lit.[22] $[\alpha]^{20}_D = -205$ (EtOH, *S* config); for analytical data, see refs 4 and 13.

Method B in Diethyl Ether. A similar protocol was followed from a 0.1 M solution of (S_{Fc},S_S)-**3a** (396 mg, 1 mmol) in freshly distilled ether at −78 °C under Ar. The transmetalation was allowed to proceed for 1 h before addition of DMF. The reaction mixture was then stirred for 2 h at −78 °C and allowed to warm to rt before quenching. A 250 mg amount of pure aldehyde (*R*)-**4a** was isolated (88% yield) after purification by FC on silica gel. Chiral HPLC analysis showed ee ≥ 99.5% for the aldehyde.

(*R*)-2-Carbomethoxy-1-(tri-*n*-butylstannyl)ferrocene (4b). According to the general procedure, sulfoxide (S_{Fc},S_S)-**3b** (613 mg, 1 mmol) was reacted with *tert*-BuLi in ether for 1 h before quenching with methyl chloroformate (3 equiv). The desired ester (*R*)-**4b** was isolated as a red oil after FC on silica gel (hexane/ether 9/1) in a 90% yield. $[\alpha]^{20}_D = 0$ ($c = 0.85$, $CHCl_3$), $[\alpha]^{20}_D = +9$ ($c = 0.68$, EtOH). From the low rotation of the ester, a chemical correlation with a known compound was done to verify the lack of racemization. Thus, a sample of the ester (*R*)-**4b** was reduced with an excess of $LiAlH_4$ in ether to the corresponding alcohol which was directly oxidized by MnO_2 in chloroform to the known (*R*)-2-formyl-1-(tri-*n*-butylstannyl)ferrocene. After preparative TLC on silica, the pure aldehyde showed $[\alpha]^{20}_D = +533$ ($c = 0.6$, EtOH), lit.[4a] $[\alpha]^{20}_D = +530$ (EtOH, *R* config). Analytical data for (*R*)-**4b**: ^{1}H NMR δ 0.9 (9H, m), 1.05 (6H, m), 1.3 (6H, m), 1.55 (6H, m), 3.72 (3H, s), 4.10 (5H, s), 4.25 (1H, m), 4.52 (1H, m), 4.95 (1H, m). ^{13}C NMR δ 10.9, 13.2, 27.4, 29.3, 51.4, 69.4, 72.2, 73.5, 73.7, 75.7, 78.1, 173.0. HRMS (EI) calcd for $C_{24}H_{38}O_2$-FeSn 534.12481, found 534.1250.

(R_{Fc},R_C) and (R_{Fc},S_C)-2-(α-Phenylmethyl)-1-(trimethylsilyl)ferrocene (4c, 4c′). According to the general procedure, sulfoxide (S_{Fc},S_S)-**3a** (400 mg, 1 mmol) was reacted with *tert*-BuLi in ether for 1 h before quenching with benzaldehyde

(22) Gokel, K.; Hoffmann, P.; Kleinmann, H. *Tetrahedron Lett.* **1970**, 1771.

(3 equiv, −78 °C 2 h and then −30 °C 1 h). FC on silica gel (hexane/ether 90/30) gave first the less polar diastereoisomer **4c** (140 mg, 40%) followed by the more polar diastereoisomer **4c′** (140 mg, 40%). The configurations on carbon were not determined. **4c**: $[\alpha]^{20}_D = -130$ ($c = 1.7$, $CHCl_3$); ^{1}H NMR δ 0.34 (9H, s), 2.03 (1H, d, $^3J = 3.8$ Hz), 3.92 (1H, m), 4.02 (5H, m), 4.13 (1H, m), 4.24 (1H, m), 5.67 (1H, d $^3J = 3.8$ Hz), 7.24−7.60 (5H, m). ^{13}C NMR δ 0.5, 68.8, 70.05, 71.2, 71.5, 73.2, 75.25, 96.1, 126.8, 127.4, 128.0, 143.1. HMSR $C_{20}H_{24}SiFeO$ 364.09459, found 364.0946. **4c′**: ^{1}H NMR δ 0.16 (9H, s), 2.43 (1H, d, $^3J = 2.4$ Hz), 4.13 (1H, m), 4.24 (5H, s), 4.34 (1H, m), 4.52 (1H, m), 5.15 (1H, d $^3J = 2.4$ Hz), 7.25 (5H, s); ^{13}C NMR δ 0.5, 68.6, 70.0, 70.9, 71.5, 74.4, 99.1, 126.8, 126.9, 127.5, 128.2, 143.3. HMSR HMSR $C_{20}H_{24}SiFeO$ 364.09459, found 364.0944.

(*R*)-2-Carbomethoxy-1-[diphenylphosphino(borane)]-ferrocene (4d). According to the general procedure, sulfoxide (S_{Fc},S_S)-**3c** (522 mg, 1 mmol) was reacted with *tert*-BuLi in ether for 1 h before quenching with methyl chloroformate (2 equiv). The reaction mixture was slowly warmed to rt (3 h) before quenching. FC on silica gel (hexane/EtOAc 4/1 gave the pure ester (*R*)-**4d** (280 mg, 64%) as a yellow solid and ferrocenyl diphenylphosphine(borane) (32 mg, 8%). Further elution with hexane/EtOAc (1/1) gave recovered sulfoxide (S_{Fc},S_S)-**3c** (133 mg, 25%). mp 166 °C; $[\alpha]^{20}_D = +14$ ($c = 1.03$, $CHCl_3$); ^{1}H NMR δ 3.46 (3H, s), 3.87 (1H, m), 4.43 (5H, s), 4.54 (1H, m), 5.15 (1H, m), 7.24−7.45 (6H, m), 7.53−7.63 (4H, m). ^{31}P NMR δ 19.76 (1P, m). ^{13}C NMR δ 51.0, 71.0, 71.5, 71.9, 75.5, 75.0, 78.2, 128.1, 128.3, 130.3, 130.6, 130.7, 131.4, (d, $J_{PC} = 19$ Hz), 132.5, 2132.9, 170.0; HRMS (EI) calcd $C_{24}H_{24}BFeO_2P$ 442.0961, found 442.0956. An enantiomeric excess of 99% was measured by HPLC on the phosphine ester obtained after removal of the borane by treatment in TFA: hexane/*i*-PrOH 95/5, 0.5 mL/min, $\lambda = 254$ nm, (*R*)-**4d** 11 min, (*S*)-**4d** 20 min.

(*S*)-2-(Diphenylphosphino)-1-(dicyclohexylphosphino-)ferrocene (4e). According to the general procedure, sulfoxide (S_{Fc},S_S)-**3c** (1.05, 2 mmol) was reacted with *tert*-BuLi in ether for 1 h at −78 °C before quenching with chlorodicyclohexylphosphine (1 g, 4.3 mmol, 2.15 equiv) and stirring at this temperature for 20 min. The reaction mixture was quenched with 20 mL of a 2 M NaOH solution and extracted with ether. After standard workup, the crude product was subjected to FC on silica gel (hexane/ether 1/1) and gave two fractions. The second fraction gave recovered starting material (S_{Fc},S_S)-**3c** (448 mg, 57% conversion). The first fraction contained the monoborane adduct of the desired product and was directly deprotected by refluxing in 10 mL of diethylamine under Ar overnight. The solution was concentrated, and the residue was purified by FC on silica gel (hexane/ether 9/1). The resulting solid was recrystallized in 10 mL of degassed ethanol and gave 213 mg of the pure diphosphine **4e** (19%) as orange crystals. $[\alpha]^{20}_D = +327$ ($c = 1.0075$, $CHCl_3$); ^{1}H NMR δ 0.5−2.0 (22H, m), 3.93 (3H, s), 4.15 (1H, m), 4.35 (1H, m), 4.47 (1H, m), 7.20−7.34 (7H, m), 7.55−7.7 (3H, m). ^{31}P NMR δ −11 (1P, d $^3J_{P-P} = 74.6$ Hz), −26 (1P, d $^3J_{P-P} = 74.6$ Hz). HRMS (EI) calcd $C_{34}H_{40}FeP_2$ 566.19546, found 566.1955.

(*S*)-2-(*p*-(Dimethylamino)phenyl)-1-(*p*-nitrophenyl)ferrocene (7). According to the general procedure for the transmetalation, 177 mg of sulfoxide (S_{Fc},S_S)-**6** (0.4 mmol) was reacted with 1.2 equiv of *tert*-BuLi in 3 mL of dry THF. Three minutes after the addition of *tert*-BuLi, 0.96 mL of a 0.5 M solution of $ZnCl_2$ in THF (Aldrich, 0.48 mmol) was introduced dropwise, and the orange solution was stirred at −78 °C for 15 min and warmed to rt. A clear yellow catalytic solution was prepared in a separate Schlenk by mixing 5.5 mg of $Pd_2(dba)_3 \cdot CHCl_3$ (12 μmol, 3% Pd) and 5.6 mg of trifurylphosphine (24 μmol, 6%) in 1 mL of dry THF under Ar for 15 min. The catalytic solution was added via canula to the ferrocenyl zinc solution followed *p*-nitroiodobenzene (130 mg, 0.52 mmol, 1.3 equiv) as a solid. The deep red reaction mixture was stirred at rt for 3 h before quenching and standard workup. Purification by FC on silica gel (cyclohexane/ether/CH_2Cl_2 85/10/5) afforded the desired complex (*S*)-**7** as a deep red solid (104 mg, 61% yield). mp 126−128 °C; $[\alpha]^{20}_D = -538$ ($c = 0.0.08$, $CHCl_3$); ^{1}H NMR δ 2.95 (6H, s), 4.07 (5H, s), 4.42 (1H, d), 4.57 (2H, d $J = 2.5$ Hz), 6.61 and 7.20 (4H, dd AB $J = 8.7$ Hz), 7.50 and 8.03 (4H, dd AB $J = 8.9$ Hz); ^{13}C NMR δ 40.4, 67.0, 68.1, 69.7, 71.1, 71.3, 82.4, 88.4, 111.8, 122.85, 124.1, 129.6, 130.5, 145.3, 147.9, 149.3; HRMS (EI) calcd $C_{24}H_{22}FeN_{22}$ 426.1031; found 426.1031.

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