A Straightforward Synthesis of (3*S*)-4-Methoxybutane-1,3-diol and its Use as Chiral Auxiliary for the Preparation of (p*S*)-1-(Diphenylphosphino)-2-formyl-1′,2′,3′,4′,5′-pentamethylferrocene

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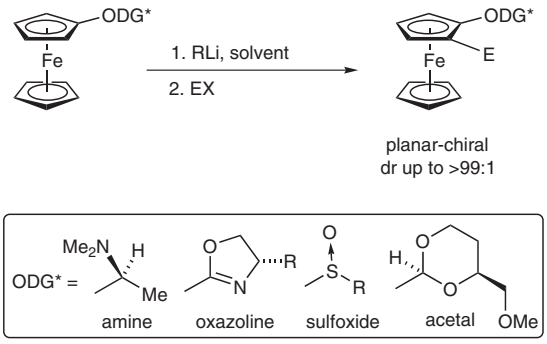
Abstract: (3*S*)-4-Methoxybutane-1,3-diol [(*S*)-**4**], an important auxiliary for the synthesis of planar-chiral metallocenes, has been obtained from (*S*)-1,2,4-butanetriol via formation of an isomerically pure acetal of *p*-nitrobenzaldehyde, O-methylation and hydrolysis. Diol (*S*)-**4** was used in a synthesis of the new planar-chiral ferrocene (p*S*)-1-(diphenylphosphino)-2-formyl-1′,2′,3′,4′,5′-pentamethylferrocene [(p*S*)-**9**].

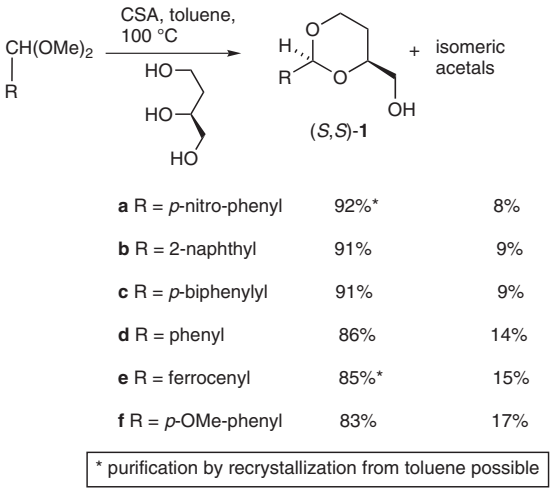
Key words: acetals, asymmetric synthesis, chiral pool, lithiation, metallocenes

Planar-chiral ferrocenes and related metallocenes have found widespread use as ligands in asymmetric catalysis.[1] The most important method for introduction of planar chirality is the directed *ortho*-lithiation induced by a chiral *ortho*-directing group (ODG*, Scheme 1) followed by reaction with an electrophile.



Scheme 1 Preparation of planar-chiral ferrocenes

In the course of an effort to prepare enantiomerically enriched 1-(diphenylphosphino)-2-formyl-1′,2′,3′,4′,5′-pentamethylferrocene (**9**, see Scheme 4), we wanted to apply the method of Kagan and co-workers,[2] who showed that lithiation of acetals derived from 4-methoxybutane-1,3-diol proceeds with very high diastereoselectivity. A drawback of this otherwise very effective method is the necessity to prepare the requisite acetals from commercially available (*R*)- or (*S*)-1,2,4-butanetriol rather than the O-methyl derivative. It is well established that dioxolanes **1** (Scheme 2) are preferentially formed by acetalization,[3] despite a variety of possible isomeric acetals.[2d] The selectivity of their formation is particularly high upon transacetalization from dimethyl acetals of aromatic aldehydes.[2,4] Kagan and coworkers found that the ferrocenyl derivative (*S*,*S*)-**1e** is crystalline and can be obtained in pure form by recrystallization after transacetalization according to Scheme 2.[2a,2b,5] The acetal was O-methylated in a standard manner, the product subjected to lithiation–electrophilic substitution, and the final acetal eventually hydrolyzed to give (*S*)-4-methoxybutane-1,3-diol.



Scheme 2 Preparation of chiral acetals (*S*,*S*)-**1a–f**

We wondered whether the procedure of Kagan and coworkers could be carried out with an aldehyde cheaper than formylferrocene in order to obtain an acetal from which 4-methoxybutane-1,3-diol could be prepared via a short route involving O-methylation and subsequent hydrolysis. By screening several acetals (*S*,*S*)-**1** (Scheme 2), it was found that the *p*-nitrophenyl derivative (*S*,*S*)-**1a** could be obtained in isomerically pure form by recrystallization from toluene. Even better results were obtained when the solvent was removed from the reaction mixture by slow distillation (over a period of 4 h), forming acetal (*S*,*S*)-**1a** quantitatively and with complete selectivity. Success with this procedure requires that the temperature in the flask, preferentially ca. 120 °C, is maintained below the melting point of (*S*,*S*)-**1a** (137–138 °C). Thus, the pro-

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cess relies on reversible transacetalization–in situ crystallization.

Methyl ether (*S*,*S*)-**3** was prepared in 82% yield directly from crude (*S*,*S*)-**1a**, contaminated with camphorsulfonic acid (CSA), by treatment with 1.2 equivalents of NaH in THF followed by reaction with 3 equivalents of methyl iodide (Scheme 3). Hydrolysis of (*S*,*S*)-**3** gave diol (*S*)-**4** as a colorless and very hygroscopic liquid. As mentioned above, compound (*S*)-**4** is known,[2b,4c] but our procedure will likely improve its availability compared to previous methods.

Diol (*S*)-**4** was used to prepare aldehyde (p*S*)-**9** (Scheme 4), which can serve as building block for the preparation of a variety of new chiral ligands, for example imines, that are of interest in homogeneous catalysis.

The achiral aldehyde **5**[6] has been previously prepared by Bildstein et al.[6a] from $Fe(acac)_2$, lithium pentamethylcyclopentadienide and sodium formyl-cyclopentadienide[7] in 46% yield. Use of $FeCl_2$[8] instead of $Fe(acac)_2$ allowed us to slightly improve the yield of **5** to 62%.

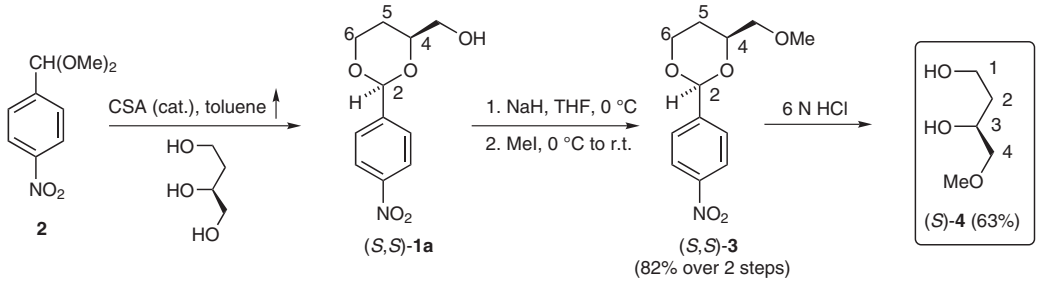
The direct acetalization of aldehyde **5** with diol (*S*)-**4** was attempted in various ways, but yields were generally unsatisfactory. Again, transacetalization solved the problem. Thus, dimethyl acetal **6** was prepared by the reaction of aldehyde **5** with $HC(OMe)_3$ and a catalytic amount of CSA in MeOH within a few minutes. The reaction of **6** with the diol (*S*)-**4** gave the desired acetal (*S*,*S*)-**7** in an excellent overall yield of 92%. Both **6** and (*S*,*S*)-**7** are very susceptible to hydrolysis and, therefore, should not be stored.

The planar-chiral phosphine (*S*,*S*,p*S*)-**8** was obtained with very high diastereomeric excess (>98%, ^1H and ^{31}P NMR) in 70% yield via metallation of (*S*,*S*)-**7** (1.1 equiv of precooled *s*-BuLi, Et_2O, –78 °C to –30 °C) followed by addition of PPh_2Cl. Finally, aldehyde (p*S*)-**9** was prepared in quantitative yield from (*S*,*S*,p*S*)-**8** by hydrolysis with *p*-TsOH in H_2O–CH_2Cl_2.

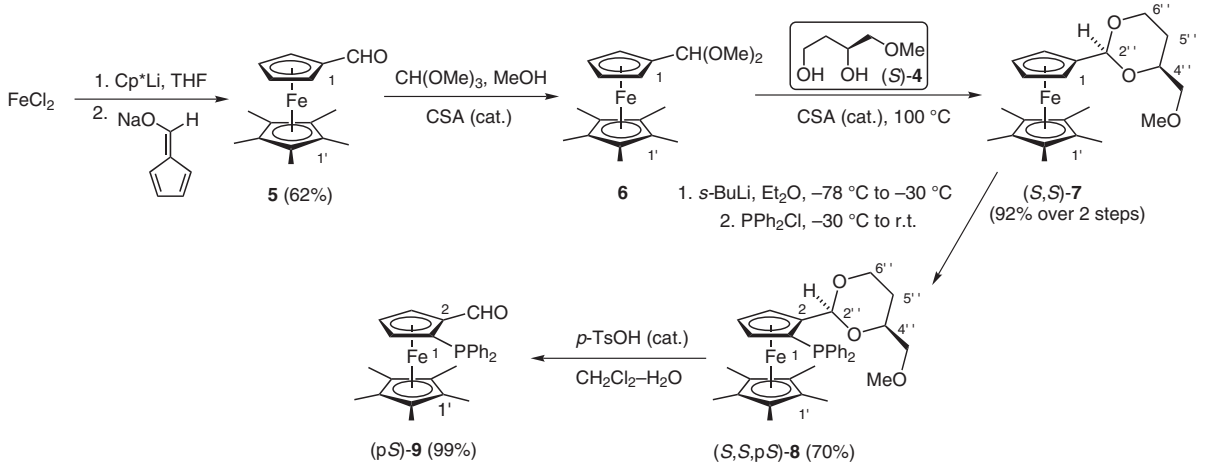
The absolute configuration of (p*S*)-**9** was assigned on the basis of an X-ray crystal structure analysis[9] and was as anticipated. An ORTEP diagram of (p*S*)-**9** is shown in Figure 1. The conformation of the molecule is obviously determined by minimization of steric interactions.

Further reactions with (*S*,*S*)-**7** and use of (p*S*)-**9** as building block for the preparation of chiral ligands for asymmetric catalysis are under active investigation in our laboratory.

Melting points were determined in open-glass capillaries and are not corrected. For all compounds ^1H NMR, $^{13}C\{^1H\}$ NMR, $^{31}P\{^1H\}$ NMR, $^1H,^1H$-gs-COSY and $^1H,^{13}C$-gs-HMQC spectra were recorded on a 300 MHz spectrometer [300 MHz (^1H), 75 MHz (^{13}C), 121 MHz (^{31}P)]. Chemical shifts are reported in δ (ppm) using residual $CHCl_3$ [7.26 (^1H), 77.36 (^{13}C)] or DMSO [2.50 (^1H), 39.52 (^{13}C)] as internal standards and H_3PO_4 as an external standard [0.00 (^{31}P)]. Mass spectra were determined on a Jeol JMX 700 spectrometer. Optical rotations were measured at r.t. with a Perkin Elmer 241 pola-



Scheme 3 *Ex chiral pool* synthesis of (*S*)-**4**



Scheme 4 Application of the diol (*S*)-**4** as a chiral auxiliary

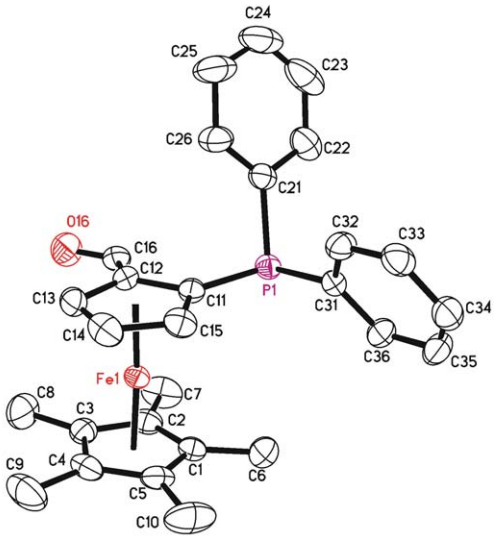


Figure 1 X-ray crystal structure of (p*S*)-**9**

rimeter. Microanalyses were performed at the Institut für Organische Chemie der Universität Heidelberg. For TLC Macherey & Nagel Polygram Sil G/UV$_{254}$ plates were used with spot detection by UV light. Macherey & Nagel Kieselgel S (0.032–0.063 mm) was used for flash chromatography. The petroleum ether used for chromatography had a boiling range of 30–75 °C. Pentamethylcyclopentadiene was prepared according to the method of Jutzi.[10] (*S*)-1,2,4-butanetriol was purchased from Lancaster. If not stated otherwise, reactions were carried out under dry argon with magnetic stirring.

1-(Dimethoxymethyl)-4-nitrobenzene (2)

A mixture of *p*-nitro-benzaldehyde (25.00 g, 165.6 mmol), MeOH (100 mL), trimethoxymethane (268 mL) and *p*-TsOH·H$_2$O (1.57 g, 8.28 mmol) was heated in an oil bath at 120 °C while distilling off the solvents over a period of ca. 1 h. The residue was distilled (bp 113 °C/1 mbar) to give 31.98 g of **2** (98%) as a light yellow oil.[11]

[(2*S*,4*S*)-2-(4-Nitrophenyl)-1,3-dioxan-4-yl]methanol [(*S*,*S*)-1a]

In a distillation apparatus, a solution of vacuum-dried (1 h, 0.05 mbar) (*S*)-1,2,4-butanetriol (10.60 g, 100.0 mmol), camphorsulfonic acid (0.21 g, 2.0 mmol) and acetal **2** (19.70 g, 100.0 mmol) in anhyd toluene (50 mL) was heated in an oil bath kept at 120 °C. Toluene was distilled off over a period of 4 h. The residue consisted of (*S*,*S*)-**1a**, which was sufficiently pure for further transformations (isomeric purity >99.5%). An analytically pure sample of (*S*,*S*)-**1a** was obtained by column chromatography (silica gel, petroleum ether–EtOAc, 1:1).

Mp 137–138 °C (white needles); R_f 0.21 (petroleum ether–EtOAc, 1:1); $[\alpha]_D^{20}$ 19.1 (*c* 0.75, EtOH).

^{1}H NMR (300 MHz, $CDCl_3$): δ = 1.50 (d, *J* = 12.5 Hz, 1 H, 5-H$_a$), 1.94 (ddd, *J* = 12.4, 7.3 Hz, 5.1 Hz, 1 H, 5-H$_b$), 2.21 (br s, 1 H, OH), 3.62–3.79 (m, 2 H, C*H*$_2$OH), 3.93–4.12 (m, 2 H, 4-H and 6-H$_a$), 4.33 (dd, *J* = 11.5, 4.9 Hz, 1 H, 6-H$_b$), 5.62 (s, 1 H, 2-H), 7.67 (d, *J* = 8.5 Hz, 2 H, ArH), 8.21 (d, *J* = 8.7 Hz, 2 H, ArH).

^{13}C NMR (75 MHz, $CDCl_3$): δ = 27.0 (C-5), 65.9 (CH_2OH), 67.0 (C-6), 78.1 (C-4), 99.9 (C-2), 123.8 (ArC), 127.6 (ArC), 145.1 (ArC$_{quart.}$), 148.5 (ArC$_{quart.}$).

HRMS: *m*/*z* calcd for $C_{11}H_{13}NO_5$ [M$^+$]: 240.0872; found: 240.0849.

Anal. Calcd for $C_{11}H_{13}NO_5$: C, 55.23; H, 5.48; N, 5.85. Found: C, 55.28; H, 5.62; N, 5.76.

(2*S*,4*S*)-4-(Methoxymethyl)-2-(4-nitrophenyl)-1,3-dioxane [(*S*,*S*)-3]

A solution of crude (*S*,*S*)-**1a** (100.0 mmol), prepared as described above, in anhyd THF (100 mL) was cooled in an ice bath. NaH (2.88 g, 120.0 mmol) was added over a period of 10 min and the resulting suspension was well stirred for further 10 min, then MeI (42.57 g, 300.0 mmol) was added dropwise. The ice bath was removed and the mixture was stirred for 12 h. Volatile materials were removed in vacuo and the residue was subjected to column chromatography (silica gel, petroleum ether–EtOAc, 1:1) to yield 20.65 g (82% over two steps) of (*S*,*S*)-**3** as a microcrystalline solid.

Mp 97–98 °C; R_f 0.45 (petroleum ether–EtOAc, 1:1); $[\alpha]_D^{20}$ 15.5 (*c* 0.73, EtOH).

^{1}H NMR (300 MHz, $CDCl_3$): δ = 1.55 (d, *J* = 13.4 Hz, 1 H, 5-H$_a$), 1.88 (ddd, *J* = 12.5, 7.4, 5.1 Hz, 1 H, 5-H$_b$), 3.41 (s, 3 H, OCH_3), 3.46 (dd, *J* = 10.3, 3.8 Hz, 1 H, C*H*$_2$OCH$_3$), 3.57 (dd, *J* = 10.4, 6.5 Hz, 1 H, C*H*$_2$OCH$_3$), 4.01 (dt, *J* = 11.8, 2.6 Hz, 1 H, 6-H$_a$), 4.12 (m$_c$, 1 H, 4-H), 4.32 (dd, *J* = 11.5, 5.0 Hz, 1 H, 6-H$_b$), 5.60 (s, 1 H, 2-H), 7.68 (d, *J* = 8.9 Hz, 2 H, ArH), 8.21 (d, *J* = 8.9 Hz, 2 H, ArH).

^{13}C NMR (75 MHz, $CDCl_3$): δ = 27.9 (C-5), 59.8 (OCH_3), 67.2 (C-6), 75.7 (CH_2OMe), 76.8 (C-4), 99.9 (C-2), 123.7 (ArC), 127.7 (ArC), 145.2 (ArC$_{quart.}$), 148.4 (ArC$_{quart.}$).

HRMS: *m*/*z* calcd for $C_{12}H_{15}NO_5$ [M$^+$]: 253.0950; found: 253.0934.

Anal. Calcd for $C_{12}H_{15}NO_5$: C, 56.91; H, 5.97; N, 5.53. Found: C, 56.85; H, 6.01; N, 5.43.

(3*S*)-4-Methoxybutane-1,3-diol [(*S*)-4]

Acetal (*S*,*S*)-**3** (20.60 g, 81.3 mmol) and 6 N HCl (81 mL) were mixed in a distillation apparatus and ca. 70 mL of H_2O were distilled off. The residue was extracted with CH_2Cl_2 (2 × 40 mL) to remove *p*-nitro-benzaldehyde and acetal (*S*,*S*)-**3** (conversion >85% as determined by ^{1}H NMR). After careful bulb-to-bulb distillation (135 °C/10 mbar) of the residual water phase 6.15 g (51.2 mmol, 63%) of diol (*S*)-**4** were obtained as a colorless liquid. The compound is hygroscopic and was stored over 4 Å MS.

$[\alpha]_D^{20}$ –21.5 (*c* 1.30, EtOH) {Lit.[4c] $[\alpha]_D^{20}$ –28.8 (*c* 0.50, $CHCl_3$)}.

^{1}H NMR (300 MHz, DMSO-d_6): δ = 1.34–1.46 (m, 1 H, 2-H$_a$), 1.49–1.61 (m, 1 H, 2-H$_b$), 3.20 (d, *J* = 5.9, 2 H, 4-H), 3.24 (s, 3 H, OCH_3), 3.48 (dd, *J* = 12.1, 5.9 Hz, 2 H, 1-H), 3.68 (m, 1 H, 3-H), 4.32 (t, *J* = 5.1 Hz, 1 H, 1-OH), 4.51 (d, *J* = 5.2 Hz, 1 H, 3-OH).

^{13}C NMR (75 MHz, DMSO-d_6): δ = 37.0 (C-2), 57.8 (C-1), 58.3 (OCH_3), 66.2 (C-3), 77.3 (C-4).

Anal. Calcd for $C_5H_{12}O_3$: C, 49.98; H, 10.07. Found: C, 49.77; H, 10.06.

1-Formyl-1′,2′,3′,4′,5′-pentamethylferrocene (5)

A: A suspension of $FeCl_2$ (10.4 g, 82.0 mmol) in THF (800 mL) was vigorously stirred in the dark for 1 h.

B: A mixture of sodium cyclopentadienide (41.0 mL of a 2.0 M solution in THF, 82.0 mmol) and methyl formate (7.6 mL, 121.8 mmol) in THF (100 mL) was stirred at r.t. for 4 h.

C: For the preparation of lithium pentamethylcyclopentadienide, *n*-BuLi (56.4 mL of a 1.6 M solution in *n*-hexane, 90.2 mmol) was added dropwise to a cooled (–78 °C) solution of pentamethylcyclopentadiene (14.1 mL, 90.2 mmol) in THF (200 mL) and the resultant mixture was stirred at r.t. for 2 h.

The suspension C was transferred via cannula to the suspension A and the mixture was stirred at r.t. for 1 h while its color turned to green. Then, suspension B was added via cannula and the resultant mixture was stirred at r.t. for 16 h. The solvents were then removed in vacuo, the residue dissolved in petroleum ether–Et_2O (1:1) and the solution filtered through a short pad of alumina (neutral, 13%

H_2O). Column chromatography (silica gel, petroleum ether–Et_2O, 2:1) afforded 16.3 g (62%) of **5** as a deep-red solid.

Mp 59–62 °C (Lit.[6b] 62.5–63 °C); R_f 0.48 (petroleum ether–Et_2O, 2:1).

^{1}H NMR (300 MHz, $CDCl_3$): δ = 1.82 (s, 15 H, CH_3), 4.15 (t, *J* = 1.7 Hz, 2 H, 3-H, 4-H), 4.25 (t, *J* = 1.7 Hz, 2 H, 2-H, 5-H), 9.69 (s, 1 H, CHO).

^{13}C NMR (75 MHz, $CDCl_3$): δ = 11.3 (CH_3), 72.2 (C-3, C-4), 77.8 (C-2, C-5), 80.5 (C-1), 82.6 (C-1′, C-2′, C-3′, C-4′, C-5′), 194.1 (CHO).

HRMS: *m*/*z* calcd for $C_{16}H_{20}OFe$ [M$^+$]: 284.0864; found: 284.0870.

Anal. Calcd for $C_{16}H_{20}OFe$: C, 67.63; H, 7.09. Found: C, 67.70; H, 7.17.

1-(Dimethoxymethyl)-1′,2′,3′,4′,5′-pentamethylferrocene (6)

A mixture of aldehyde **5** (2.84 g, 10.0 mmol), MeOH (6 mL), trimethyl orthoformate (16 mL) and camphorsulfonic acid (0.05 g, 0.2 mmol) was stirred for 5 min, then volatiles were removed in vacuo. The residue, which contained **6**, CSA and traces of trimethyl orthoformate, was directly used for the preparation of (*S*,*S*)-**7** (see below). An analytically pure sample of **6** was obtained by quick column chromatography (silica gel, petroleum ether–EtOAc–Et_3N, 10:10:1) as an orange oil. The compound is very susceptible to hydrolysis.

R_f 0.98 (petroleum ether–EtOAc–Et_3N, 10:10:1, yellow spot).

^{1}H NMR (300 MHz, $CDCl_3$): δ = 1.87 (s, 15 H, CH_3), 3.21 (s, 6 H, OCH_3), 3.67 (t, *J* = 2.2 Hz, 2 H, 3-H, 4-H), 3.77 (t, *J* = 2.1 Hz, 2 H, 2-H, 5-H), 5.31 [s, 1 H, C*H*(OCH_3)$_2$].

^{13}C NMR (75 MHz, $CDCl_3$): δ = 11.3 (CH_3), 51.7 (OCH_3), 69.8 (C-3, C-4), 72.2 (C-2, C-5), 80.7 (C-1′, C-2′, C-3′, C-4′, C-5′), 84.3 (C-1), 101.4 [*C*H(OCH_3)$_2$].

HRMS: *m*/*z* calcd for $C_{18}H_{26}O_2Fe$ [M$^+$]: 330.1282; found: 330.1281.

1-[(2*S*,4*S*)-4-(Methoxymethyl)-1,3-dioxan-2-yl]-1′,2′,3′,4′,5′-pentamethylferrocene [(*S*,*S*)-7]

A mixture of crude compound **6** (see above, 10.0 mmol), CSA (0.2 mmol) and freshly distilled diol (*S*)-**4** (1.22 g, 10.2 mmol) was heated at 100 °C for 4 h. Conversion was monitored by TLC. Volatiles were removed in vacuo and the residue was purified by column chromatography (silica gel, petroleum ether–EtOAc–Et_3N, 16:4:1) to yield 3.56 g (92% over 2 steps) of (*S*,*S*)-**7** as an orange-brown oil.

R_f 0.33 (petroleum ether–EtOAc–Et_3N, 16:4:1, yellow spot); $[\alpha]_D^{20}$ –51.2 (*c* 0.85, $CHCl_3$).

^{1}H NMR (300 MHz, $CDCl_3$): δ = 1.44–1.55 (m, 1 H, 5″-H_a), 1.69–1.83 (m, 1 H, 5″-H_b), 1.88 (s, 15 H, CH_3), 3.41 (s, 3 H, OCH_3), 3.41 (dd, *J* = 10.1, 4.9 Hz, 1 H, C*H*$_2$$OCH_3$), 3.55 (dd, *J* = 10.1, 5.9 Hz, 1 H, C*H*$_2$$OCH_3$), 3.65 (br s, 2 H, 3-H, 4-H), 3.79, 3.83 (2 br s, 2 H, 2-H, 5-H), 3.91 (dt, *J* = 12.2, 2.6 Hz, 1 H, 6″-H_a), 3.95–4.05 (m, 1 H, 4″-H), 4.21 (dd, *J* = 11.3, 5.1 Hz, 1 H, 6″-H_b), 5.28 (s, 1 H, 2″-H).

^{13}C NMR (75 MHz, $CDCl_3$): δ = 11.4 (CH_3), 28.4 (C-5″), 59.7 (OCH_3), 66.9 (C-6″), 69.0 (C-3, C-4), 72.6 (C-2, C-5), 76.0 (*C*$H_2$$OCH_3$), 76.2 (C-4″), 80.8 (C-1′, C-2′, C-3′, C-4′, C-5′), 85.3 (C-1), 100.3 (C-2″).

HRMS: *m*/*z* calcd for $C_{21}H_{30}O_3Fe$ [M$^+$]: 386.1544; found: 386.1553.

Anal. Calcd for $C_{21}H_{30}O_3Fe$: C, 65.29; H, 7.83. Found: C, 65.53; H, 7.93.

(p*S*)-1-(Diphenylphosphino)-2-[(2*S*,4*S*)-4-(methoxymethyl)-1,3-dioxan-2-yl]-1′,2′,3′,4′,5′-pentamethylferrocene [(*S*,*S*,p*S*)-8]

A cold (–78 °C) solution of acetal (*S*,*S*)-**7** (3.50 g, 9.06 mmol) in anhyd Et_2O (45 mL) was treated dropwise with a precooled (ca. –70 °C) 1.3 M solution of *s*-BuLi (9.97 mmol) in cyclohexane (7.67 mL). The reaction mixture was then allowed to warm up to –30 °C within 1 h. A light-red precipitate appeared. At this temperature P-chlorodiphenylphosphine (2.20 g, 9.97 mmol) was added dropwise, and the reaction mixture was allowed to warm up to r.t. over a period of 12 h. Solvents were removed in vacuo and the residue was subjected to column chromatography (silica gel, petroleum ether–EtOAc–Et_3N, 16:4:1) to yield 3.61 g (70%) of (*S*,*S*,p*S*)-**8** as a microcrystalline yellow solid.

Mp >120 °C (dec.); R_f 0.39 (petroleum ether–EtOAc–Et_3N, 16:4:1, yellow spot); $[\alpha]_D^{20}$ –245 (*c* 0.88, $CHCl_3$).

^{1}H NMR (300 MHz, $CDCl_3$): δ = 1.34–1.43 (m, 1 H, 5″-H_a), 1.55–1.70 (m, 1 H, 5″-H_b), 1.76 (s, 15 H, CH_3), 2.70–2.83 (m, 2 H, C*H*$_2$$OCH_3$), 3.08 (s, 3 H, OCH_3), 3.49 (m_c, 1 H, 4-H), 3.66 (m_c, 1 H, 4″-H), 3.75–3.84 (m, 1 H, 6″-H_a), 3.83 (t, *J* = 2.4 Hz, 1 H, 3-H), 4.13–4.17 (m, 1 H, 5-H), 4.18 (dd, *J* = 11.3 Hz, 3.8 Hz, 1 H, 6″-H_b), 5.37 (d, *J* = 1.8 Hz, 1 H, 2″-H), 7.08–7.18 (m, 5 H, Ph), 7.30–7.37 (m, 3 H, Ph), 7.61–7.69 (m, 2 H, Ph).

^{13}C NMR (75 MHz, $CDCl_3$): δ = 11.3 (CH_3), 28.5 (C-5″), 59.4 (OCH_3), 66.9 (C-6″), 73.5 (C-5), 74.2 (C-4), 74.8 (C-3), 75.0 (*C*$H_2$$OCH_3$), 75.5 (C-4″), 77.6 (C-2), 81.4 (C-1′, C-2′, C-3′, C-4′, C-5′), 89.1 ($^1J_{C,P}$ = 19.4 Hz, C-1), 99.8 (C-2″), 127.4, 127.6, 127.7, 128.1, 128.3, 129.4, 132.9, 133.1, 136.3, 136.6 (Ph).

^{31}P NMR (121 MHz, $CDCl_3$): δ = –25.8.

HRMS: *m*/*z* calcd for $C_{33}H_{39}O_3PFe$ [M$^+$]: 570.1986; found: 570.2012.

Anal. Calcd for $C_{33}H_{39}O_3PFe$: C, 69.48; H, 6.89; P, 5.43. Found: C, 69.46; H, 6.89; P, 5.36.

(p*S*)-1-(Diphenylphosphino)-2-formyl-1′,2′,3′,4′,5′-pentamethylferrocene [(p*S*)-9]

A mixture of degassed CH_2Cl_2 (12 mL), degassed H_2O (12 mL), acetal (*S*,*S*,p*S*)-**8** (3.50 g, 6.14 mmol) and *p*-TsOH·H_2O (0.06 g, 0.32 mmol) was stirred for 12 h at r.t. The organic phase was separated and the aqueous phase extracted twice with CH_2Cl_2. The organic phases were combined, dried over Na_2SO_4 and the solvents were removed in vacuo to yield 2.85 g (99%) of aldehyde (p*S*)-**9** as orange plates.

Mp 149–150 °C; R_f 0.38 (petroleum ether–EtOAc, 4:1); $[\alpha]_D^{20}$ 429 (*c* 0.19, EtOH).

^{1}H NMR (300 MHz, $CDCl_3$): δ = 1.75 (s, 15 H, CH_3), 3.80 (m_c, 1 H, 4-H), 4.29 (t, *J* = 2.5 Hz, 1 H, 3-H or 5-H), 4.50 (m_c, 1 H, 3-H or 5-H), 7.08–7.15 (m, 2 H, Ph), 7.16–7.23 (m, 3 H, Ph), 7.33–7.43 (m, 3 H, Ph), 7.58–7.68 (m, 2 H, Ph), 9.78 (d, *J* = 2.6 Hz, 1 H, CHO).

^{13}C NMR (75 MHz, $CDCl_3$): δ = 11.2 (CH_3), 74.4 (C-3 or C-5), 79.2 (C-3 or C-5), 79.4 (C-4), 80.4 ($^1J_{C,P}$ = 16.6 Hz, C-1), 83.1 (C-1′, C-2′, C-3′, C-4′, C-5′), 83.4 ($^2J_{C,P}$ = 11.1 Hz, C-2), 128.4, 128.5, 128.5, 128.6, 128.6, 129.9, 132.3, 132.6, 136.1, 136.4 (Ph), 136.9 ($^1J_{C,P}$ = 11.8 Hz, Ph-$C_{quart.}$), 140.5 ($^1J_{C,P}$ = 12.5 Hz, Ph-$C_{quart.}$), 193.1 (CHO).

^{31}P NMR (121 MHz, $CDCl_3$): δ = –28.5.

HRMS: *m*/*z* calcd for $C_{28}H_{29}OPFe$ [M$^+$]: 468.1306; found: 468.1324.

Anal. Calcd for $C_{28}H_{29}OPFe$: C, 71.81; H, 6.24; P, 6.61. Found: C, 71.81; H, 6.18; P, 6.66.

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(9) Crystal Data for (p*S*)-**9**: $C_{28}H_{29}FeOP$, MW = 468.33, monoclinic, space group $P2_1/c$, a = 9 3345 (1) Å, b = 14 1901 (2) Å, c = 27 7268 (3) Å, β = 98 691 (1)°, V = 3630.45 (8) Å^3, Z = 6, D_{calcd} = 1.285 g/cm^3, crystal size 0.28 × 0.26 × 0.26 mm^3. Intensity data were collected at 200(2) K with Mo-K_α radiation (λ = 0.71073 Å). A total of 16501 independent reflections were measured in range $0.74 < \Theta < 26.00°$ and 14474 reflections were considered as observed applying the condition $I > 2\sigma(I)$. The crystal used for X-ray diffraction was grown in a solution of CH_2Cl_2 and pentane. All calculations were performed using the SHELXL-97 program. Structure solved by direct methods and refined against F^2 with a Full-matrix least-squares algorithm. Hydrogen atoms were treated using appropriate riding models. Flack absolute structure parameter 0.002 (9), goodness of fit 1.02 for observed reflections, final residual values $R1$ (F) = 0.040, $wR2$ (F^2) = 0.096 for observed reflections, residual electron density –0.47 to 1.13 e Å^{-3}. CCDC 296455 contains the supplementary crystallographic data for this structure. The data can be obtained free of charge via www.ccdc.cam.ac.uk/conts/retrieving.html (or from the CCDC, 12 Union Road, Cambridge, CB2 1EZ, UK; fax: +44 1223 336033; email: deposit@ccdc.cam.ac.uk).

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