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On the role of planar chirality in asymmetric catalysis: Improvement of enantioselectivity in the addition of diethylzinc to aldehydes with planar chiral 1,1′-*N*,*O*-ferrocenyl ligands

Ming Li, Ke Yuan, Yang-Yang Li, Bo-Xun Cao, Jie Sun and Xue-Long Hou*

State Key Laboratory of Organometallic Chemistry, Shanghai Institute of Organic Chemistry, Chinese Academy of Sciences, 354 Fenglin Lu, Shanghai 200032, China

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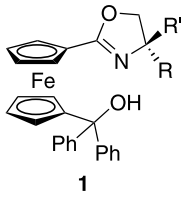
Abstract—A series of novel planar chiral 1,1′-*N*,*O*-ferrocenyl ligands have been synthesized, and applied as catalysts in asymmetric diethylzinc additions to aldehydes. The results indicate that the planar chirality had great impact on the reaction outcome.

1. Introduction

Since the pioneering work of Hayashi et al.,[1] the use of planar chiral ferrocene ligands as well as the role of planar chirality has received more attention recently.[2] However, the role of planar chirality was still unclear. Some examples have shown that the planar chirality had a significant effect on the enantioselectivity,[3] while in other examples it was not so apparent.[4] Recently, we reported the synthesis of 1,1′-disubstituted ferrocenes and their applications in asymmetric catalysis and provided experimental evidence to show why the planar chirality is important and how it works.[5] Now we provide another example to show the great impact of planar chirality on the enantioselective outcome in addition reactions of diethylzinc reagent to aldehydes.

2. Results and discussions

Recently, we reported the synthesis of chiral 1,1′-*N*,*O*-ferrocenyl ligands **1** (Scheme 1) and their application in the addition of diethylzinc to aldehydes, where up to 90.9% e.e. was achieved.[6] To show the role of planar chirality in these ligands, the ligands with planar chirality **2a**–**d** were synthesized. As shown in Scheme 2, ferrocenyloxazoline derivatives **6**[7] were treated with *n*-BuLi in THF at −78°C, followed by the addition of benzophenone, then trapped with chlorotrimethylsilane to afford silyl ether **4** in good yield. *ortho*-Lithiation[8] of **4** and subsequent treatment with methyl iodide gave 2-substituted compounds. Conversion of these to the target ligands **2** was accomplished by removing the TMS group with TBAF in THF at reflux.



1

(*S*)-**1a** R=*i*-Pr, R'=H
(*S*)-**1b** R=*t*-Bu, R'=H
(*S*)-**1c** R=Bn, R'=H
(*R*)-**1d** R=H, R'=Ph

Scheme 1.

Ligands **3** with different planar chirality configurations were synthesized by temporarily blocking the preferred *ortho*-position with TMS. Deprotonation at the remaining *ortho*-position of silylated ferrocene (*S*,*Sp*)-**5**, followed by the reaction of lithiated intermediate with methyl iodide and removal of the TMS protection group with TBAF, furnished **3** as single diastereoisomer in moderate overall yield (Scheme 3).

All new ferrocenes are air-stable solids that gave satisfied analytical and spectroscopic data. The absolute configuration of planar chirality of ferrocene **2b** was confirmed by X-ray diffraction and the configuration of it is assigned as (*S*,*Rp*) (Fig. 1).

* Corresponding author. E-mail: xlhou@mail.sioc.ac.cn

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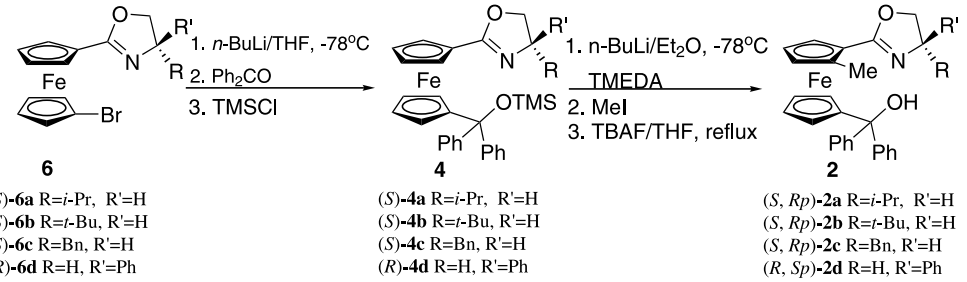
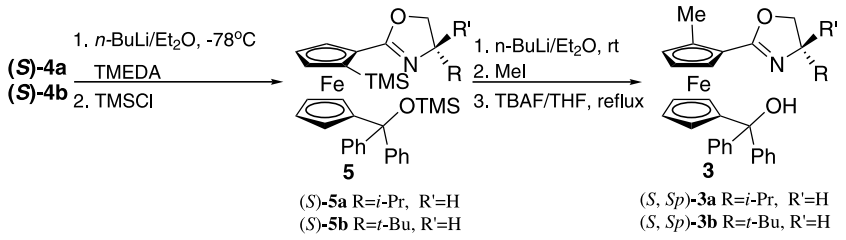


Scheme 2.



Scheme 3.

In the presence of a catalytic amount of planar chiral 1,1′-*N*,*O*-ferrocenes **2**, the reaction of benzaldehyde with diethyl zinc[9] proceeded smoothly to provide the corresponding alcohol (Eq. (1)). The results are shown in Table 1. It can be seen that the e.e. values obtained from all ligands **2** are higher than those obtained from ferrocenes **1** without planar chirality. When ligand **2b** was used, 94.9% e.e. was given while only 88.6% e.e. was provided when using corresponding **1b** without planar chirality (entry 2).[6] These exciting results encouraged us to probe whether this improvement existed in other aldehydes

Thus, a variety of aldehydes were employed subsequently with ferrocene (*S*,*Rp*)-**2b**. All results were showed in Table 2. For comparative purposes, the results from ligand (*S*)-**1b** without planar chirality are also given.[6]

As expected, a remarkable improvement in the e.e. value was made for all tested aldehydes. When *trans*-cinnamaldehyde was the substrate, the enantiomeric excess increased from 64.2% to 87.4% (entry 6); and 95.4% e.e. was obtained when *p*-tolualdehyde was the substrate (entry 3). These results reveal great positive effect of planar chirality on improving enantioselectivity in this reaction.

Next, attention was turned to the impact of configuration of planar chirality on the stereochemistry of the reaction. As shown in Table 3, a dramatic drop in enantioselectivity of the reaction was observed when 'mismatched' ferrocene (*S*,*Sp*)-**3a** was used as ligand instead of (*S*,*Rp*)-**2a**, the absolute configuration of corresponding alcohols was also converted to (*S*)- from (*R*)- (entries 2 and 4). It seemed that the planar chirality plays an important role in the reaction.[5] To our surprise, however, when using (*S*,*Sp*)-**3b** as ligand, the e.e. values were just a little lower than those obtained from ferrocene (*S*,*Rp*)-**2b**, and the configurations of products remain as (*R*)- (entries 6 and 8). These results might reflect the different steric effect on the reaction caused by the group on the ferrocene ring and on the oxazoline ring with different size. In ligand **3b**, the *tert*-butyl group is far bulkier than the methyl group, so that the steric hindrance of methyl group is relatively ineffective. While in ligands (*S*,*Rp*)-**2a** and (*S*,*Sp*)-**3a**, the isopropyl group is not bulky enough, so the methyl group could show its effect on the stereochemical con-

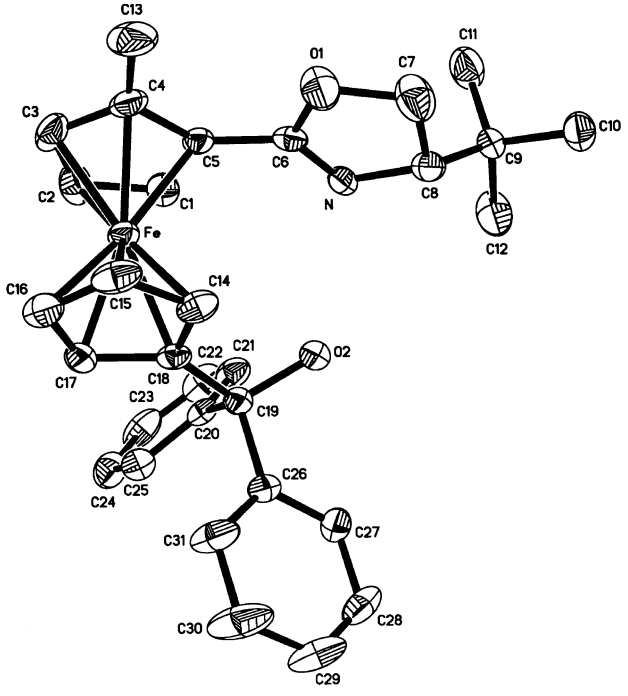
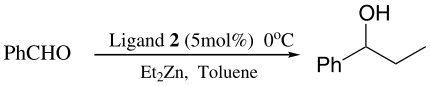


Figure 1. ORTEP illustration of **2b** with atomic numbering.

Table 1. Enantioselective addition of diethylzinc to benzaldehyde using **2a–d** as ligands

(1)



Entry	Ligands	Yield (%)[a]	e.e. (%)[b]	Ligands	e.e. (%)[b,d]	Config.[c]
1	(*S*,*Rp*)-**2a**	96	**83.2**	(*S*)-**1a**	80.9	*R*
2	(*S*,*Rp*)-**2b**	93	**94.9**	(*S*)-**1b**	88.6	*R*
3	(*S*,*Rp*)-**2c**	95	**77.0**	(*S*)-**1c**	71.6	*R*
4	(*R*,*Sp*)-**2d**	91	**83.4**	(*R*)-**1d**	81.5	*S*

[a] Isolated yield based on aldehyde.
[b] Determined by HPLC (Chiralcel OD column).
[c] Configurations were assigned by comparison with the sign of the specific rotation of known compounds.
[d] Ref. 6.

Table 2. Enantioselective addition of diethylzinc to aldehydes with ligand (*S*,*Rp*)-**2b**

Entry	Aldehydes	Yield (%)[a]	e.e. (%)[b]	e.e. (%)[c]	Config.[d]
1	*p*-ClC_6H_4CHO	91	**95.3**	89.3	*R*
2	*p*-BrC_6H_4CHO	96	**96.2**	90.9	*R*
3	*p*-MeC_6H_4CHO	93	**95.4**		*R*
4	*p*-$MeOC_6H_4CHO$	94	**94.1**	86.6	*R*
5	1-Naphthaldehyde	91	**93.8**	89.9	*R*
6	PhCH=CHCHO	89	**87.4**	64.2	*R*

[a] Isolated yield based on aldehyde with **2b**.
[b] Obtained from **2b** and determined by HPLC (Chiralcel OD column).
[c] Obtained from **1b**.[6]
[d] Configurations were assigned by comparison with the sign of the specific rotation of known compounds.

Table 3. Enantioselective addition of diethylzinc to aldehydes with different planar chiral ligands

Entry	Aldehydes	Ligands	Yield (%)[a]	e.e. (%)[b]	Config.[c]
1	C_6H_5CHO	(*S*,*Rp*)-**2a**	96	83.2	*R*
2	C_6H_5CHO	(*S*,*Sp*)-**3a**	94	**37.0**	***S***
3	*p*-BrC_6H_4CHO	(*S*,*Rp*)-**2a**	97	85.7	*R*
4	*p*-BrC_6H_4CHO	(*S*,*Sp*)-**3a**	94	**33.4**	***S***
5	C_6H_5CHO	(*S*,*Rp*)-**2b**	93	94.9	*R*
6	C_6H_5CHO	(*S*,*Sp*)-**3b**	95	**92.2**	***R***
7	*p*-BrC_6H_4CHO	(*S*,*Rp*)-**2b**	96	96.2	*R*
8	*p*-BrC_6H_4CHO	(*S*,*Sp*)-**3b**	92	**93.0**	***R***

[a] Isolated yield based on aldehyde.
[b] Determined by HPLC (Chiralcel OD column).
[c] Configurations were assigned by comparison with the sign of the specific rotation of known compounds.

trol. Although the process of this reaction is not clear, it is obvious that the stereochemistry is determined by cooperation of central chirality and planar chirality.

3. Conclusion

In summary, ferrocenyl ligands **2** and **3** with different configurations of planar chirality were synthesized. The e.e. values were improved when using these ferrocenes ligands in diethylzinc addition to aldehyde, comparing to that using ligands **1**. The stereochemistry of this reaction was controlled by central chirality and planar chirality together and the planar chirality shows its significant impact on the stereochemistry of the reaction. Further studies on the relationship of the group attached on the oxazoline ring and Cp ring and the applications of these ligands in asymmetric synthesis are in progress.

4. Experimental

4.1. General

All of the reactions were performed under dry argon atmosphere. Toluene, diethyl ether and THF were freshly distilled from sodium. Reagents were used without further purification, except for the aldehydes which were redistilled before use. Melting points were uncor-

rected. ^{1}H NMR spectra were recorded on a Varian AMX-300 (300 MHz) spectrometer in $CDCl_3$ at room temperature. Chemical shifts were given in parts per million downfield from tetramethylsilane. Optical rotations were measured on Perkin–Elmer341MC polarimeter with a thermally jacketed 10 cm cell at 20°C (concentration c given as g/100 mL). IR spectra were recorded in KBr and measured in cm^{-1}, using a Shimadzu IR-440 infrared spectrophotometer. Mass spectra were taken using HP 5989A mass spectrometers. Elemental analyses were performed on a Foss–Heraeus Vario EL instrument. Enantiomeric excess were determined by chiral HPLC on a Chiralcel OD column.

4.2. 1-[(*S*)-4-Isopropyl-2,5-oxazolinyl]-1′-(α-diphenyltrimethylsiloxymethyl)ferrocene (*S*)-4a

A solution of **6a** (1.23 g, 3.3 mmol) in THF (20 mL) was cooled to −78°C and treated with *n*-butyl lithium (1.6 M in hexane, 2.1 mL, 3.3 mmol). The mixture was stirred for an additional 30 min, benzophenone (727 mg, 4 mmol) was added and stirred at same temperature for 4 h. Chlorotrimethylsilane (521 mg, 4.8 mmol) was added and the resulting mixture was stirred at 0°C for 20 min. Saturated $NaHCO_3$ (20 mL) was added and the mixture was extracted with dichloromethane (3×20 mL), the organic layer was washed with brine (2×30 mL) and dried over Na_2SO_4. After the solvent was removed under reduced pressure, the residue was purified by column chromatography (silica gel, ethyl acetate/petroleum 1:8) to afford **4a** (1.54 g, 85%) as orange oil. $[\alpha]_D^{20}=-82.6$ (c 0.16, $CHCl_3$). ^{1}H NMR (300 MHz, $CDCl_3$): δ −0.10 (s, 9H); 0.91 (d, $J=6.7$ Hz, 3H); 0.98 (d, $J=6.7$ Hz, 3H); 1.69–1.85 (m, 1H), 3.90–4.02 (m, 4H); 4.12–4.25 (m, 5H); 4.51–4.53 (m, 2H); 7.20–7.26 (m, 10H). MS m/z: 551 (M^+, 100), 552 (28), 306 (59), 220 (60). IR (KBr): 2956, 1657, 1485, 1445, 1251, 1104, 1072, 889, 839, 702 cm^{-1}. Anal. calcd for $C_{32}H_{37}FeNO_2Si$: C, 69.68; H, 6.76; N, 2.54. Found: C, 69.77; H, 6.83; N, 2.45.

4.3. 1-[(*S*)-4-*tert*-Butyl-2,5-oxazolinyl]-1′-(α-diphenyltrimethylsiloxymethyl)ferrocene (*S*)-4b

Compound **6b** (546 mg, 1.4 mmol) was allowed to react according to the procedure for **4a** to afford **4b** (640 mg, 81%) as orange oil. $[\alpha]_D^{20}=-116$ (c 0.28, $CHCl_3$). ^{1}H NMR (300 MHz, $CDCl_3$): δ −0.09 (s, 9H); 0.94 (s, 9H); 3.86 (dd, $J=7.8$, 10.1 Hz, 1H); 3.93–3.96 (m, 2H); 4.08–4.14 (m, 2H); 4.16–4.20 (m, 2H); 4.21–4.24 (m, 2H); 4.52 (t, $J=1.9$ Hz, 2H); 7.23–7.27 (m, 10H). MS m/z 565 (M^+, 100), 566 (82), 564 (22), 320 (49), 220 (76); IR (KBr): 2954, 1656, 1445, 1251, 1116, 1098, 1071, 491 cm^{-1}. Anal. Calcd for $C_{33}H_{39}FeNO_2Si$: C, 70.08; H, 6.95; N, 2.48. Found: C, 70.06; H, 6.96; N, 2.35.

4.4. 1-[(*S*)-4-Benzyl-2,5-oxazolinyl]-1′-(α-diphenyltrimethylsiloxymethyl)ferrocene (*S*)-4c

Compound **6c** (680 mg, 1.6 mmol) was allowed to react according to the procedure for **4a** to afford **4c** (702 mg, 73%) as orange oil. $[\alpha]_D^{20}=-14$ (c 0.15, $CHCl_3$). ^{1}H NMR (300 MHz, $CDCl_3$): δ −0.09 (s, 9H), 2.65 (dd, $J=9.1$ Hz, 13.9 Hz, 1H), 3.19 (dd, $J=4.4$ Hz, 13.7 Hz, 1H), 3.97–4.04 (m, 3H), 4.14–4.22 (m, 5H), 4.38–4.42 (m, 1H), 4.58 (s, 2H), 7.20–7.34 (m, 15H); MS (EI) m/z (rel.) 599 (M^+, 100), 600 (48), 510 (34), 354 (58), 220 (57), 91 (23); IR (KBr): 3087, 2955, 1654, 1603, 1251, 1104, 1073, 493 cm^{-1}. Anal. calcd for $C_{36}H_{37}FeNO_2Si$: C, 72.11; H, 6.22; N, 2.34. Found: C, 71.83; H, 6.43; N, 2.27.

4.5. 1-[(*R*)-4-Phenyl-2,5-oxazolinyl]-1′-(α-diphenyltrimethylsiloxymethyl)ferrocene (*R*)-4d

Compound **6d** (410 mg, 1.0 mmol) was allowed to react according to the procedure for **4a** to afford **4d** (370 mg, 63%) as orange oil. $[\alpha]_D^{20}=+97.2$ (c 0.35, $CHCl_3$); ^{1}H NMR (300 MHz, $CDCl_3$): δ −0.10 (s, 9H), 4.00 (s, 2H), 4.11–4.20 (m, 3H), 4.27 (s, 2H), 4.60–4.66 (m, 3H), 5.15–5.18 (m, 1H), 7.26–7.37 (m, 15H); MS (EI) m/z (rel.) 585 (M^+, 85), 586 (39), 583 (15), 340 (100), 220 (70); IR (KBr): 3087, 2956, 1652, 1602, 1492, 1251, 1112, 1073, 491 cm^{-1}. Anal. calcd for $C_{35}H_{35}FeNO_2Si$: C, 71.79; H, 6.02; N, 2.39. Found: C, 71.90; H, 6.31; N, 2.26.

4.6. 1-[(*S*)-4-Isopropyl-2,5-oxazolinyl]-1′-(α-diphenylhydroxymethyl)-2-(*Rp*)-methylferrocene (*S*,*Rp*)-2a

A solution of ferrocene **4a** (330 mg, 0.6 mmol), TMEDA (84 mg, 0.72 mmol) in 6 mL of Et_2O was cooled to −78°C and treated with *n*-BuLi (1.6 M in hexane, 0.45 mL, 0.72 mmol). After being stirred for 2 h at this temperature, methyl iodide (199 mg, 1.4 mmol) was added and the mixture was stirred at 0°C for an additional 1 h. The reaction mixture was quenched with water (10 mL), extracted with ethyl ether (3×10 mL), combined the organic phase and washed with brine (2×10 mL), dried over Na_2SO_4. After removal of the solvent under reduced pressure, the residue was purified by flash column chromatography with ethyl acetate: petroleum (60–90°C, 1:10) as an eluent to afford orange oil. The oil was directly dissolved in 10 mL of THF and TBAF (1.0 M in THF, 6 mL, 6 mmol) was added. After the mixture was refluxed for 8 h, water (10 mL) was added and extracted with dichloromethane (3×20 mL), washed with brine (2×10 mL), dried over Na_2SO_4. After removal of the solvent under reduced pressure, the residue was purified by column chromatography with ethyl acetate: petroleum (60–90°C, 1:5) as an eluent to afford **2a** (222 mg, 73%) as orange solid; mp 110–112°C. $[\alpha]_D^{20}=-281$ (c 0.24, $CHCl_3$); ^{1}H NMR (300 MHz, $CDCl_3$): 0.96 (d, $J=6.8$ Hz, 3H), 1.04 (d, $J=6.8$ Hz, 3H), 1.77–1.88 (m, 1H), 2.17 (s, 3H), 3.82–3.83 (m, 1H), 3.91–3.92 (m, 1H), 4.03–4.13 (m, 3H), 4.21–4.22 (m, 3H), 4.32–4.35 (m, 1H), 4.69 (s, 1H), 7.12–7.50 (m, 10H); MS (EI) m/z (rel.) 493 (M^+, 92), 494 (33), 263 (100), 245 (61), 229 (43), 177 (47); IR (KBr): 3503, 2918, 1666, 1492, 1017, 1001, 486 cm^{-1}. Anal. calcd for $C_{30}H_{31}FeNO_2$: C, 73.03; H, 6.33; N, 2.84. Found: C, 72.89; H, 6.16; N, 2.84.

4.7. 1-[(*S*)-4-*tert*-Butyl-2,5-oxazolinyl]-1′-(α-diphenylhydroxymethyl)-2-(*Rp*)-methylferrocene (*S*,*Rp*)-2b

Compound **4b** (340 mg, 0.6 mmol) was allowed to react according to the procedure for **2a** to afford **2b** (243 mg, 80%) as an orange solid; mp 156–158°C. $[\alpha]_D^{20}=-358$ (*c* 0.27, $CHCl_3$); ^1H NMR (300 MHz, $CDCl_3$): δ 0.99 (s, 9H), 2.19 (s, 3H), 3.80 (s, 1H), 3.91 (s, 1H), 4.00–4.06 (m, 2H), 4.13–4.23 (m, 5H), 4.65–4.72 (m, 1H), 5.05 (br, 1H), 7.11–7.24 (m, 6H), 7.31–7.36 (m, 2H), 7.48–7.51 (m, 2H); MS (EI) *m*/*z* (rel.) 507 (M^+, 25), 508 (24), 230 (77), 229 (100), 148 (44); IR (KBr): 3313, 2961, 1639, 1491, 1307, 1217, 1083, 490 cm^{-1}. Anal. calcd for $C_{31}H_{33}FeNO_2$: C, 73.37; H, 6.55; N, 2.76. Found: C, 73.39; H, 6.65; N, 2.70.

4.8. 1-[(*S*)-4-Benzyl-2,5-oxazolinyl]-1′-(α-diphenylhydroxymethyl)-2-(*Rp*)-methylferrocene (*S*,*Rp*)-2c

Compound **4c** (360 mg, 0.6 mmol) was allowed to react according to the procedure for **2a** to afford **2c** (208 mg, 64%) as an orange solid; mp 52–55°C. $[\alpha]_D^{20}=-224$ (*c* 0.10, $CHCl_3$); ^1H NMR (300 MHz, $CDCl_3$): δ 2.17 (s, 3H), 2.74 (dd, $J=8.2$ Hz, 13.6 Hz, 1H), 3.14 (dd, $J=5.1$ Hz, 13.7 Hz, 1H), 3.87 (t, $J=5.3$ Hz, 1H), 3.91–3.93 (m, 1H), 4.04–4.07 (m, 1H), 4.09–4.12 (m, 2H), 4.16–4.18 (m, 1H), 4.21–4.23 (m, 1H), 4.28 (t, $J=9.0$ Hz, 1H), 4.47–4.57 (m, 1H), 4.67–4.68 (m, 1H), 4.82 (s, 1H), 7.24–7.35 (m, 13H), 7.45–7.47 (m, 2H); MS (EI) *m*/*z* (rel.) 541 (M^+, 77), 542 (31), 311 (34), 293 (100), 229 (32), 91 (68); IR (KBr): 3526, 3085, 2920, 1647, 1602, 1444, 1152, 1017, 492 cm^{-1}. Anal. calcd for $C_{34}H_{31}FeNO_2$: C, 75.42; H, 5.77; N, 2.59. Found: C, 75.21; H, 6.06; N, 2.46.

4.9. 1-[(*R*)-4-Phenyl-2,5-oxazolinyl]-1′-(α-diphenylhydroxymethyl)-2-(*Sp*)-methylferrocene (*R*,*Sp*)-2d

Compound **4d** (350 mg, 0.6 mmol) was allowed to react according to the procedure for **2a** to afford **2d** (212 mg, 67%) as an orange solid; mp 128–130°C. $[\alpha]_D^{20}=+284$ (*c* 0.10, $CHCl_3$); ^1H NMR (300 MHz, $CDCl_3$): δ 2.22 (s, 3H), 3.91 (s, 1H), 3.95 (s, 1H), 4.10–4.33 (m, 6H), 4.65–4.76 (m, 2H), 5.31 (br, 1H), 7.15–7.25 (m, 6H), 7.29–7.47 (m, 9H); MS (EI) *m*/*z* (rel.) 527 (M^+, 16), 105 (53), 77 (56), 43 (100); IR (KBr): 3295, 2903, 1633, 1601, 1491, 1218, 1077, 4 cm^{-1}. Anal. calcd for $C_{33}H_{29}FeNO_2$: C, 75.15; H, 5.54; N, 2.66. Found: C, 75.17; H, 5.76; N, 2.52.

4.10. 1-[(*S*)-4-Isopropyl-2,5-oxazolinyl]-1′-(α-diphenyltrimethylsiloxymethyl)-2-(*Sp*)-trimthylsilylferrocene (*S*,*Sp*)-5a

A solution of ferrocene **4a** (550 mg, 1.0 mmol), TMEDA (139 mg, 1.2 mmol) in 12 mL of Et_2O was cooled to −78°C and treated with *n*-BuLi (0.75 mL, 1.2 mmol, 1.6 M in hexane). After stirring for 2 h at this temperature, chlorotrimethylsilane (152 mg, 1.4 mmol) was added and the mixture was stirred at 0°C for an additional 1 h. The reaction mixture was quenched with saturated $NaHCO_3$ (10 mL), then extracted with ethyl ether (3×10 mL) and washed with brine (2×10 mL) and dried over Na_2SO_4. After removing the solvent under vacuum, the residue was purified by column chromatography with ethyl acetate: petroleum (60–90°C, 1:10) as an eluent to afford **5a** (576 mg, 93%) as orange oil. $[\alpha]_D^{20}=+49$ (*c* 0.195, $CHCl_3$); ^1H NMR (300 MHz, $CDCl_3$): δ −0.11 (s, 9H), 0.19 (s, 9H), 0.90 (d, $J=6.73$ Hz, 3H), 1.00 (d, $J=6.74$ Hz, 3H), 1.73–1.81 (m, 1H), 3.59 (s, 1H), 3.84–3.96 (m, 3H), 4.12–4.25 (m, 5H), 4.63 (s, 1H), 7.12–7.31 (m, 10H); MS (EI) *m*/*z* (rel.) 623 (M^+, 100), 624 (55), 378 (19), 292 (25); IR (KBr): 2957, 2898, 1656, 1492, 1445, 1263, 1251, 1102, 1072, 505 cm^{-1}. Anal. calcd for $C_{35}H_{45}FeNO_2Si_2$: C, 67.39; H, 7.27; N, 2.25. Found: C, 66.90; H, 7.27; N, 2.18.

4.11. 1-[(*S*)-4-*tert*-Butyl-2,5-oxazolinyl]-1′-(α-diphenyltrimethylsiloxymethyl)-2-(*Sp*)-trimthylsilylferrocene (*S*,*Sp*)-5b

Compound **4b** (900 mg, 1.6 mmol) was allowed to react according to the procedure for **5a** to afford **5b** (901 mg, 89%) as orange oil. $[\alpha]_D^{20}=+129$ (*c* 0.09, $CHCl_3$); ^1H NMR (300 MHz, $CDCl_3$): δ −0.11 (s, 9H), 0.19 (s, 9H), 0.94 (s, 9H), 3.68–3.69 (m, 1H), 3.85 (dd, $J=8.1$ Hz, 9.9 Hz, 1H), 3.92 (t, $J=2.4$ Hz, 1H), 4.03 (t, $J=8.4$ Hz, 1H), 4.10–4.14 (m, 1H), 4.17–4.21 (m, 3H), 4.24–4.26 (m, 1H), 4.64–4.65 (m, 1H), 7.12–7.25 (m, 5H), 7.26–7.29 (m, 5H); MS (EI) *m*/*z* (rel.) 637 (M^+, 100), 638 (99), 392 (17), 292 (56), 229 (22), 73 (17); IR (KBr): 3088, 2955, 1658, 1492, 1263, 1251, 1141, 1072, 491 cm^{-1}. Anal. calcd for $C_{36}H_{47}FeNO_2Si_2$: C, 67.80; H, 7.43; N, 2.20. Found: C, 67.82; H, 7.45; N, 2.11.

4.12. 1-[(*S*)-4-Isopropyl-2,5-oxazolinyl]-1′-(α-diphenylhydroxymethyl)-2-(*Sp*)-methylferrocene (*S*,*Sp*)-3a

Ferrocene **5a** (310 mg, 0.5 mmol) was dissolved in 6 mL of Et_2O at room temperature and treated with *n*-BuLi (0.38 mL, 0.6 mmol, 1.6 M in hexane). After stirring for 1 h at this temperature, methyl iodide (1.2 mmol) was added and the mixture was stirred for an additional 1 h. The reaction mixture was quenched with water (10 mL) and extracted with ethyl ether (3×10 mL), washed with brine (2×10 mL) and dried over Na_2SO_4. After removing the solvent under in vacuum, the residue was purified by flash column chromatography with ethyl acetate: petroleum (60–90°C, 1:30) as an eluent to afford orange oil. The product was directly dissolved in 6 mL of THF and TBAF (5 mL, 5 mmol, 1.0 M in THF) was added to the solution. After the mixture was refluxed for 8 h, water (5 mL) was added and extracted with dichloromethane (3×10 mL), washed with brine (2×10 mL), dried over Na_2SO_4. After removing the solvent under in vacuum, the residue was purified by column chromatography with ethyl acetate: petroleum (60–90°C, 1:5) as an eluent to afford **3a** (165 mg, 67%) as orange foam; mp 50–53°C. $[\alpha]_D^{20}=+136$ (*c* 0.23, $CHCl_3$); ^1H NMR (300 MHz, $CDCl_3$): 0.90 (d, $J=6.7$ Hz, 3H), 1.04 (d, $J=6.7$ Hz, 3H), 1.77–1.84 (m, 1H), 2.15 (s, 3H), 3.83–4.03 (m, 4H), 4.10–4.32 (m, 5H), 4.68–4.76 (m, 2H), 7.15–7.47 (m, 8H), 7.47–7.50 (m, 2H); MS (EI) *m*/*z* (rel.) 493 (M^+, 100), 492 (73), 494

(33), 263 (53), 245 (53), 229 (52); IR (KBr): 3525, 2958, 1639, 1600, 1490, 1074, 1018, 489 cm^{-1}. Anal. calcd for $C_{30}H_{31}FeNO_2$: C, 73.03; H, 6.33; N, 2.84. Found: C, 73.00; H, 6.38; N, 2.85.

4.13. 1-[(*S*)-4-*tert*-Butyl-2,5-oxazolinyl]-1′-(α-diphenylhydroxymethyl)-2-(*Sp*)-methylferrocene (*S*,*Sp*)-3b

Compound **5b** (890 mg, 1.4 mmol) was allowed to react according to the procedure for **3a** to afford **3b** (340 mg, 48%) as an orange solid; mp 125–126°C. $[\alpha]_D^{20} = +127$ (*c* 0.15, $CHCl_3$); ^1H NMR (300 MHz, $CDCl_3$): δ 0.93 (s, 9H), 2.15 (s, 3H), 3.78–3.84 (m, 1H), 3.94–3.97 (m, 2H), 4.06–4.13 (m, 2H), 4.17–4.23 (m, 4H), 4.70 (s, 1H), 4.82 (br, 1H), 7.14–7.33 (m, 8H), 7.47–7.50 (m, 2H); MS (EI) *m*/*z* (rel.) 507 (M^+, 34), 508 (33), 229 (100), 202 (36), 148 (30); IR (KBr): 3318, 2954, 1655, 1445, 1105, 1078, 489 cm^{-1}. Anal. calcd for $C_{31}H_{33}FeNO_2$: C, 73.37; H, 6.55; N, 2.76. Found: C, 73.40; H, 6.70; N, 2.71.

4.14. General procedure for catalytic asymmetric addition of diethylzinc to various aldehydes

To a solution of ferrocene ligand **2** (0.05 mmol) in toluene (2.5 mL) was added Et_2Zn (2.0 mL, 2.0 mmol, 1.0 M in hexane) at room temperature. After 30 min, the reaction system was cooled to 0°C, and the aldehyde (1.0 mmol) was added under an argon atmosphere. After being stirred for the appropriate time, the reaction was quenched with 3 M HCl. The mixture was extracted with diethyl ether (3×5 mL). The organic layer was washed with brine (2×5 mL), dried over Na_2SO_4 and evaporated under reduced pressure to give an oily residue. Purification of the residue by column chromatography gave the optically active alcohol. The enantiomeric excess was determined by HPLC analysis using a Chiralcel OD column. Configurations were assigned by comparison with the sign of specific rotation of known compounds.

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