Synthesis of chiral diferrocenyl dichalcogenides and their application to asymmetric nucleophilic ring opening of *meso*-epoxides

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Four novel optically active bis[(*R,S*)- and (*S,R*)-2-(1-dimethylaminoethyl)ferrocenyl] dichalcogenides [abbreviated as (*R,S*)- and (*S,R*)-$(Fc^*E)_2$ (E = S and Te)], each of which possesses two axial and two central elements of chirality, have been prepared by lithiation of commercially available chiral (1-dimethylaminoethyl)ferrocenes, followed by treatment with elemental sulfur or tellurium and air oxidation, in 42–65% isolated yields. The structure of the di-(*S,R*)-ferrocenyl disulfide has been fully characterized by X-ray crystallography. Ferrocenyl chalcogenide anions (Fc^*E^-) produced by reduction of the above $(Fc^*E)_2$ and the known $(Fc^*Se)_2$ with $LiAlH_4$ in tetrahydrofuran are found to act as useful stereoselective nucleophiles for ring opening of *meso*-epoxides such as cyclohexene oxide, cyclopentene oxide, cyclooctene oxide and *cis*-stilbene oxide to give the corresponding ferrocenyl β-hydroxyalkyl chalcogenides in high yields with up to 71% diastereoisomeric excess (de). Although the diastereoselectivity depends on the combination of chalcogen atom and *meso*-epoxide, it is generally higher with E = S and Se than with E = Te. Selenoxide elimination of (*S,R*)-2-(1-dimethylaminoethyl)ferrocenyl 2-hydroxycyclohexyl selenide (66% de), obtained by the ring opening of cyclohexene oxide with (*S,R*)-$(Fc^*Se)_2$, gives (*S*)-cyclohex-2-enol with 60% ee. The *S*-configuration suggests that the ring opening, by the nucleophilic attack of the chiral ferrocenyl chalcogenide anion on the epoxide carbon, mainly occurs *via* the least hindered transition state considering the interactions between the epoxide, the 1-dimethylaminoethyl moiety and the ferrocene.

We are currently interested in asymmetric synthesis using newly prepared chiral diferrocenyl dichalcogenides as reagents and ligands. For example [2,3]sigmatropic rearrangement giving chiral allylic alcohols,[1] selenoxide elimination giving chiral allenic compounds,[2] rhodium(I)-catalysed asymmetric hydrosilylation of ketones using these dichalcogenides as chiral ligands[3] and diastereoselective oxyselenenylation of alkenes with the chiral ferrocenylselenenyl bromide,[4] have been studied. The last example shows a high diastereoselectivity in an electrophilic reaction. In order to understand the molecular recognition ability shown by these dichalcogenides in nucleophilic reactions,[5,6] we investigated the nucleophilic ring-opening reaction of *meso*-epoxides by the ferrocenyl chalcogenide anions and managed to obtain ferrocenyl β-hydroxyalkyl chalcogenides in high yield with up to 71% de. The results of this study are reported here.

Results and discussion

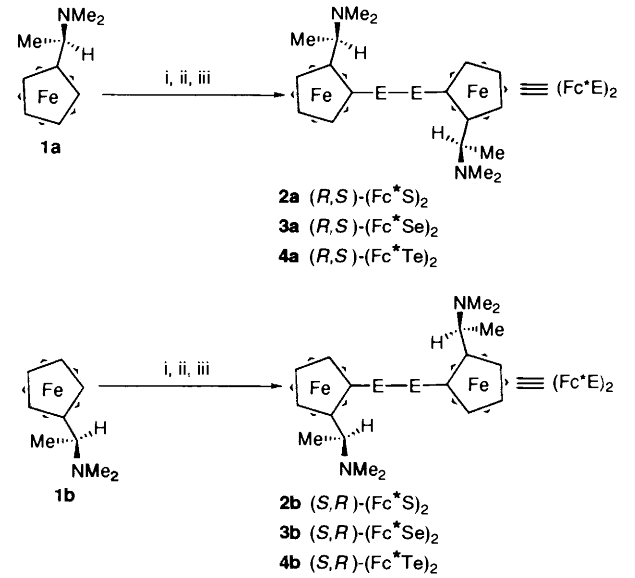
Synthesis of chiral bis[2-(1-dimethylaminoethyl)ferrocenyl] dichalcogenides

Following the preparative method described for chiral bis[2-(1-dimethylaminoethyl)ferrocenyl] diselenides, (*R,S*) and (*S,R*)-$(Fc^*Se)_2$† **3**,[1] the corresponding sulfur and tellurium analogues [(*R,S*)- and (*S,R*)-$(Fc^*E)_2$ (E = S, Te)] (**2** and **4**, respectively) were similarly prepared from (*R*)- and (*S*)-(1-dimethylaminoethyl)ferrocenes **1** as an orange solid (51–65%) and a black solid (42–47%), respectively (Scheme 1). As the lithiation of the ferrocene occurred highly diastereoselectively (94% de),[1] one purification by column chromatography afforded pure compounds **2** and **4**. The structure of (*S,R*)-$(Fc^*S)_2$ **2b** was fully characterized by X-ray crystallography and its absolute configuration was clarified to be *S,R*, where the configurations at the chiral carbon of the dimethylaminoethyl substituent and around the ferrocene axis are *S* and *R*, respectively (Fig. 1).[1,7] Selected bond distances and angles for **2b** are presented in Table 1. The torsional angle of C(1)–S(1)–S(2)–C(15) is 94.3° which is similar to that of 94.1° for (*S,R*)-$(Fc^*Se)_2$ **3b**,[1] showing no size effect of the chalcogen atom on the torsional angle. As in the case of **3b**, where no interaction between Se and N atoms was observed, there was no interaction between S and N atoms in **2b**: the atomic distances between S and N atoms were 4.07 Å [S(1)–N(1)] and 3.78 Å [S(2)–N(2)] and larger than the sum of their van der Waals radii (3.39 Å). In accordance with this fact, the methyl protons of the dimethylamino group appeared as a singlet peak in the ¹H NMR spectrum.

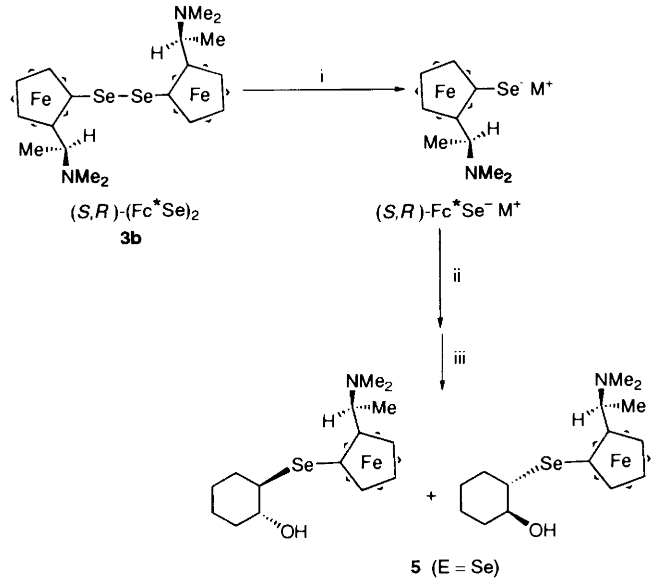
Table 1 Selected bond distances and bond angles for **2b**

Bond distances (Å)			
S(1)–S(2)	2.071(2)	S(2)–C(15)	1.760(5)
S(1)–C(1)	1.737(5)	C(15)–C(16)	1.436(7)
C(1)–C(2)	1.444(7)	C(16)–C(25)	1.495(7)
C(2)–C(11)	1.506(9)	C(25)–C(26)	1.511(8)
C(11)–C(12)	1.55(1)	C(25)–N(2)	1.451(8)
C(11)–N(1)	1.466(9)		
Bond angles (deg)			
S(2)–S(1)–C(1)	103.9(2)	S(1)–S(2)–C(15)	103.2(2)
C(1)–C(2)–C(11)	125.9(5)	C(15)–C(16)–C(25)	126.2(5)
C(2)–C(11)–N(1)	115.3(6)	C(16)–C(25)–N(2)	109.8(5)
C(2)–C(11)–C(12)	112.4(6)	C(16)–C(25)–C(26)	111.6(5)
C(11)–N(1)–C(13)	114.2(7)	C(25)–N(2)–C(27)	121.3(7)
C(11)–N(1)–C(14)	118.3(9)	C(25)–N(2)–C(28)	111.7(6)

† For convenience, Fc* is used as an abbreviation for 2-(1-dimethylaminoethyl)ferrocenyl. The dichalcogenides are abbreviated as (*R,S*)- and (*S,R*)-$(Fc^*E)_2$. In the stereochemical descriptors (*R,S*) and (*S,R*), the first configuration refers to the chiral carbon of the dimethylaminoethyl substituent and the second configuration refers to planar chirality around the ferrocene axis.



Scheme 1 *Reagents:* i, Bu^sLi in Et_2O; ii, E (E = S, Se, Te); iii, H_2O, air oxidation



Scheme 2 *Reagents:* i, reducing reagent in solvent; ii, cyclohexene oxide; iii, H_2O

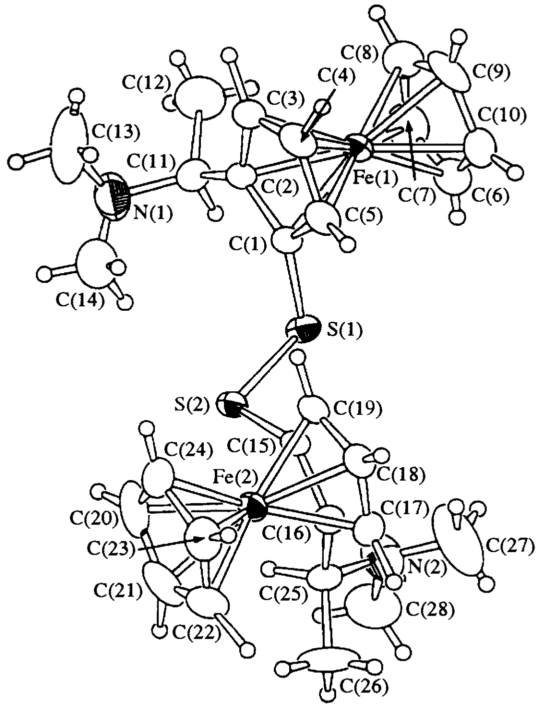


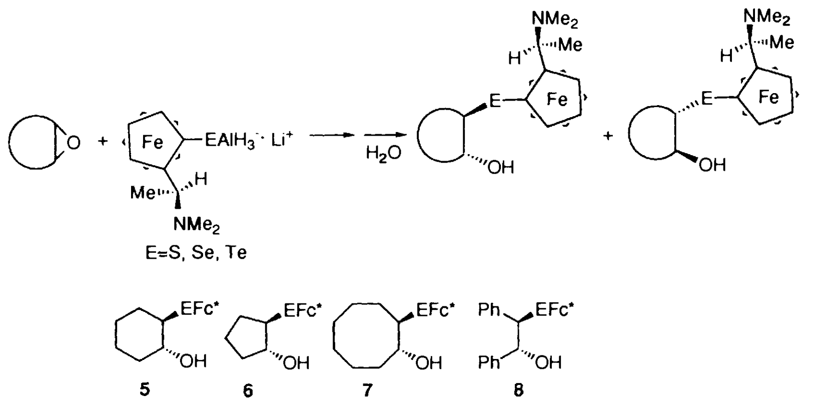
Fig. 1 Crystal structure of **2b**

Asymmetric ring opening of *meso*-epoxides using chiral diferrocenyl dichalcogenides

(*S*,*R*)-Ferrocenyl selenide anions produced *in situ* by reduction of (*S*,*R*)-$(Fc^*Se)_2$ with a variety of reductants such as $LiAlH_4$,[8] $NaBH_4$,[9] $LiBH_4$, DIBAL-H[10] and SmI_2[11] were treated with cyclohexene oxide in dry ethanol or tetrahydrofuran (THF) at −20–+50 °C (Scheme 2). The product was a diastereoisomeric mixture of the corresponding *trans*-ferrocenyl β-hydroxycyclohexyl selenides **5** (E = Se). First, we chose $NaBH_4$ as a reductant because it is known to be useful in the reductive cleavage of chiral di-binaphthyl diselenide,[5] but the value of the diastereoisomeric excess (de) was only 2–11% (Table 2). The reaction did not proceed in methanol as solvent. Next, $LiBH_4$, DIBAL-H, and SmI_2 were used as reductants. The reaction with $LiBH_4$ afforded **5** (E = Se), but with a very low de value as in the case of $NaBH_4$, while it did not proceed with DIBAL-H. With SmI_2 in THF moderate selectivities (27–58% de) were observed at 0–25 °C. When $LiAlH_4$ was employed as a reductant, however, a high yield of **5** (E = Se) with a higher de (66% de) was produced at 25 °C in THF. The higher reaction temperature was more effective than the lower one (69% de at 40 °C; 9% de at −20 °C), but the chemical yield was slightly lower. In an attempt to improve the de value, the reactions were carried out at 25 °C for 10–20 h in the presence of various additives such as TMEDA (39% de, 63% yield), Bu_3P (8% de, 98% yield) and 18-crown-6 (45% de, 54% yield) and also in diethyl ether as solvent (16% de, 62% yield), but no improvement was observed in any of the cases. The results are shown in Table 2.

Although the reaction conditions have not yet been optimized, the use of $LiAlH_4$ in THF at 25 °C for 20 h was revealed to be the best for obtaining a high yield of **5** (E = Se) with high stereoselectivity among the examined experiments. The ring opening of various epoxides was carried out with three (*S*,*R*)-dichalcogenides under these conditions. The results are shown in Table 3 (Scheme 3). The yield of the ring-opened product was quite high in all cases irrespective of the kind of chalcogen atom and the epoxide, but the de value was very dependent on them. In the case of cyclopentene oxide, the reaction with a nucleophile with a larger-size chalcogen atom resulted in lower selectivities (S > Se > Te; 71, 44 and 41% de, respectively). For cyclooctene oxide and *cis*-stilbene oxide, a similar tendency was observed (cyclooctene oxide, S = Se > Te; 40, 43 and 21% de; *cis*-stilbene oxide, S > Se > Te; 45, 33 and 13% de). However, different results were obtained for cyclohexene oxide. The use of diselenide gave the best result (66% de) with this compound and with disulfide and ditelluride the selectivity was quite low (10 and 8% de). All the results are reproducible and, thus, there is no obvious correlation between chalcogen size and the de value.

In order to investigate the reaction pathway, it was necessary to confirm the configuration of the ring-opened product **5** (E = Se) (66% de). Because of difficulties in determining the absolute configuration of **5** (E = Se) itself, we carried out selenoxide elimination of its benzoate to obtain cyclohex-2-enyl benzoate **9** (60% ee) (Scheme 4), the absolute configuration of which was determined to be *S* by HPLC analysis using a Daicel Chiralcel OB column by comparison with authentic samples.[12] When the selenium nucleophile attacks the epoxide carbon atom from



Scheme 3

Table 2 Asymmetric ring opening reaction of cyclohexene oxide using compound **3b**[a]

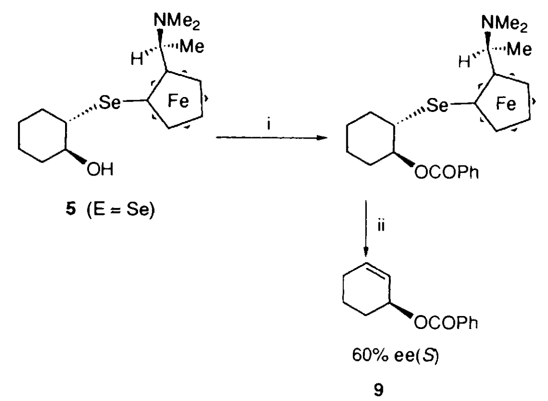
Run	Reductant	Solvent	Temp./time (°C)/(h)	Isolated yield (%) of product, **5** (E = Se)	de (%)[b]
1	$NaBH_4$	EtOH	25/40	78	2
2	$NaBH_4$	EtOH	−20/40	71	11
3	$NaBH_4$	EtOH	50/5	99	7
4	$NaBH_4$[c]	EtOH	25/20	79	8
5	$NaBH_4$[d]	EtOH	25/15	86	0
6	$LiBH_4$	EtOH	25/70	81	9
7	$LiBH_4$	EtOH	0/70	58	13
8	$LiBH_4$[e]	EtOH	25/20	84	7
9	DIBAL-H	THF	0/40	0	—
10	DIBAL-H	THF	25/50	12	6
11	SmI_2	THF	25/15	98	27
12	SmI_2	THF	0/15	33	58
13	SmI_2[f]	THF	25/15	70	30
14	SmI_2	THF	−20/40	0	—
15	$LiAlH_4$	THF	25/20	94	66
16	$LiAlH_4$	THF	40/5	75	69
17	$LiAlH_4$	THF	−20/20	82	9

[a] All the reactions were carried out in the presence of cyclohexene oxide (0.5 mmol) and **3b** (0.25 mmol) with reductant (0.5 mmol). [b] The de value was determined by ^1H NMR. [c] $NaBH_4$ (2.5 mmol) was used. [d] Tributylphosphine (0.5 mmol) was added. [e] 18-Crown-6 (0.5 mmol) was added. [f] HMPA (0.5 mmol) was added.

Table 3 Asymmetric ring opening reaction of *meso*-epoxide using **2b**–**4b** and $LiAlH_4$ in THF[a]

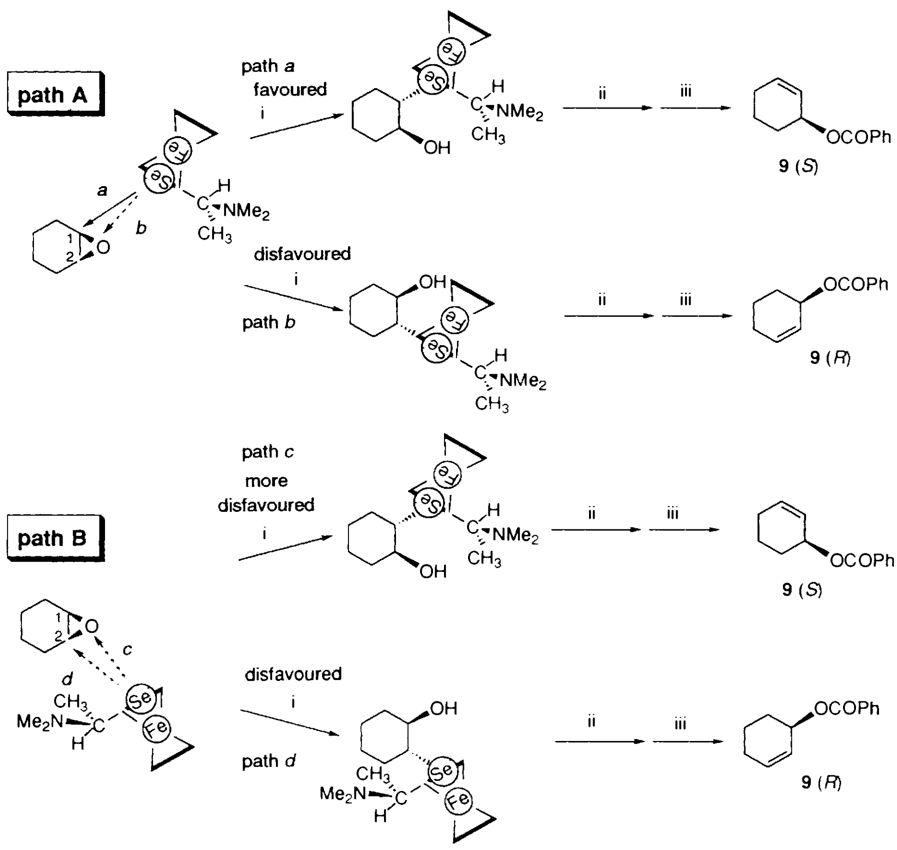
Run	Epoxide	$(Fc^*E)_2$	Temp./time (°C)/(h)	Yield (%)[b]	de (%)[c]
1	Cyclopentene	**2b**	25/15	97	71
2	Cyclopentene	**3b**	25/20	88	44
3	Cyclopentene	**4b**	25/20	84	41
4	Cyclohexene	**2b**	25/15	92	10
5	Cyclohexene	**3b**	25/20	94	66
6	Cyclohexene	**4b**	25/20	89	8
7	Cyclooctene	**2b**	25/15	84	40[d]
8	Cyclooctene	**3b**	25/20	77	43
9	Cyclooctene	**4b**	25/20	88	21[d]
10	Stilbene	**2b**	25/15	86	45
11	Stilbene	**3b**	25/20	84	33
12	Stilbene	**4b**	25/20	83	13[d]

[a] All the reactions were carried out in the presence of epoxide (0.5 mmol) and **2b**–**4b** (0.25 mmol) with $LiAlH_4$ (0.5 mmol) in THF. [b] Isolated yield of **5**, **6**, **7** and **8**. [c] The de value was determined by ^1H NMR. [d] In this case, addition of [Eu(hfc)$_3$] was needed to determine the de.



Scheme 4 *Reagents:* i, PhCOCl; ii, H_2O_2 in CH_2Cl_2

behind, at least four possible transition states should be considered as shown in Scheme 5. The selenide can approach the carbon either with the bulky side chain on the ferrocene on the opposite side of the epoxide (path A) or with the bulky group on the same side as the epoxide (path B). In each case there is a choice of two approaches as shown in paths *a* and *b*, and in paths *c* and *d*, for paths A and B, respectively. By considering the steric repulsion in paths A and B, the former should clearly be the more favourable path. In path A, (*S*)-**9** is obtained *via* path *a* and (*R*)-**9** *via* path *b*. Path *a* is more favoured than path *b* here because of the increasing interaction between 1-H and the selenide anion in path *b* and, in fact, compound (*S*)-**9** was obtained as the major product as expected. The axial chirality of the ferrocene seems to play the most important role in this stereoselection.



Scheme 5 *Reagents:* i, H_2O; ii, PhCOCl; iii, H_2O_2 in CH_2Cl_2

In conclusion, four chiral diferrocenyl disulfides and ditellurides having planar as well as central chirality have been prepared and they and the known selenium analogue $(Fc^*E)_2$ (E = S, Se, Te) were applied to diastereoselective ring opening of *meso*-epoxides for the first time. In most cases, except for cyclohexene oxide, the diastereoselectivity was found to increase in the order Te < Se < S.

Experimental

^1H (270 MHz) and ^{13}C NMR (67.8 MHz) spectra were recorded on a JEOL GSX-270 spectrometer for solutions in $CDCl_3$. Chemical shifts were reported in δ units downfield from the internal reference Me_4Si. Coupling constants J are given in Hz. Melting points are uncorrected. GLC analyses were performed on 1 m × 3 mm stainless steel column packed with 20% PEG on Shimalite and 25 m HiCap-CBP-10-S25 capillary column with flame-ionization detectors and N_2 as carrier gas. Column chromatographies on Al_2O_3 were performed with ICN Alumina N, Akt. I (hexane and hexane–ethyl acetate eluents). Elemental analyses were performed at Microanalytical Center of Kyoto University. $[\alpha]_D$ Values are given in units of 10^{-1} deg cm^2 g^{-1}. All the solvents were distilled from CaH_2 or $LiAlH_4$ and stored over 4 Å molecular sieves under N_2. All epoxides were commercial reagents and distilled just before use. The (*R*)-(+)-*N*,*N*-dimethyl-1-ferrocenylethylamine **1a** and (*S*)-(−)-*N*,*N*-dimethyl-1-ferrocenylethylamine **1b** are commercially available, but they were also easily prepared by the reported method on a large scale.[13]

Preparation of bis[(*R*,*S*)-2-(1-dimethylaminoethyl)ferrocenyl] disulfide 2a

The synthesis of the sulfide **2a** was carried out by the following procedure. After lithiation of **1a** (3.42 g, 13 mmol) with Bu^sLi (15 mmol) in dry diethyl ether (50 cm^3) at 0 °C under N_2, sulfur powder (0.43 g, 13 mmol) was added portionwise to the resulting mixture which was then stirred at 0 °C for 3 h. The mixture was poured into water and then air was bubbled through the solution at room temperature for 5 h. The title compound **2a** was isolated as an orange solid (1.94 g, 6.7 mmol, 51%) by column chromatography on active alumina with ethyl acetate as eluent (Scheme 1), mp 169–170 °C (from hexane); δ_H 4.30–4.47 (6 H, m, C_5H_3), 4.07 (10 H, s, C_5H_5), 3.80 (2 H, q, J 6.87, CH), 2.22 [12 H, s, $N(CH_3)_2$] and 1.50 (6 H, d, J 6.87, $CHCH_3$); δ_C 91.1 [s, $CCH(CH_3)N$], 82.4 (s, CS), 74.2 (d, C_5H_3), 70.1 (d, C_5H_5), 68.6 (d, C_5H_3), 68.4 (d, C_5H_3), 55.5 (d, CH), 41.5 [q, $N(CH_3)_2$] and 18.6 (q, $CHCH_3$) (Found: C, 58.4; H, 6.3; N, 4.8. $C_{28}H_{36}Fe_2N_2S_2$ requires C, 58.34; H, 6.30; N, 4.86%); $[\alpha]_D^{30}$ −650 (*c* 0.100, $CHCl_3$).

Bis[(*S*,*R*)-2-(1-dimethylaminoethyl)ferrocenyl] disulfide 2b

This compound was similarly prepared from **1b** as an orange solid (65%), mp 172–173 °C (from hexane) (Found: C, 58.3; H, 6.4; N, 4.8. $C_{28}H_{36}Fe_2N_2S_2$ requires C, 58.34; H, 6.30; N, 4.86%); $[\alpha]_D^{30}$ +650 (*c* 0.104, $CHCl_3$).

X-Ray structure determination of compound 2b (Fig. 1, Table 1)

Data for **2b** (an orange crystal, grown in hexane), $C_{28}H_{36}Fe_2N_2S_2$, were collected on a Rigaku AFC7R diffractometer with graphite monochromated Mo-Kα radiation (λ = 0.710 69 Å) and a 12 kW rotating anode generator. Crystal data for **2b** are as follows: orthorhombic, space group $P2_12_12_1$; a = 14.955(1), b = 17.350(1), c = 10.855(3) Å; V = 2816.5(7) Å^3; Z = 4; D_c = 1.36 g cm^{-3}; μ(Mo-Kα) = 11.96 cm^{-1}; total of 4581 reflections within 2θ = 60.0°. The final R value was 0.044 (R_w = 0.051). The structure was solved by the direct method (SHELXS86). All non-hydrogen atoms were refined anisotropically. Hydrogen atom positions were geometrically calculated or taken from a difference Fourier map. Atomic coordinates, bond lengths and angles and thermal parameters have been deposited at the Cambridge Crystallographic Data Centre.‡

Preparation of chiral bis[2-(1-dimethylaminoethyl)ferrocenyl] ditelluride 4

Ditellurides **4a** and **4b** were similarly prepared by the addition of tellurium powder in place of sulfur powder. Bis[(*R*,*S*)-2-(1-dimethylaminoethyl)ferrocenyl] ditelluride **4a** was isolated as a black solid (42%), mp 55–56 °C; δ_H 4.48 (2 H, q, *J* 1.30, C_5H_3), 4.23 (2 H, q, *J* 1.10, C_5H_3), 4.18 (2 H, q, *J* 1.30, C_5H_3), 4.06 (10 H, s, C_5H_5), 4.01 (2 H, q, *J* 6.90, CH), 2.18 [12 H, s, $N(CH_3)_2$] and 1.25 (6 H, d, *J* 6.90, $CHCH_3$); δ_C 93.7 [s, $CCH(CH_3)N$], 76.2 (d, C_5H_3), 70.7 (d, C_5H_5), 67.7 (d, C_5H_3), 67.1 (d, C_5H_3), 59.5 (d, CH), 50.2 (s, CTe), 39.7 [q, $N(CH_3)_2$] and 9.6 (q, $CHCH_3$) (Found: C, 43.5; H, 4.8; N, 3.5. $C_{28}H_{36}Fe_2N_2Te_2$ requires C, 43.82; H, 4.73; N, 3.65%); $[\alpha]_D^{25}$ −620 (*c* 1.00, $CHCl_3$).

Bis[(*S*,*R*)-2-(1-dimethylaminoethyl)ferrocenyl] ditelluride 4b

Isolated as a black solid (47%), mp 57–58 °C (Found: C, 43.9; H, 4.9; N, 3.6. $C_{28}H_{36}Fe_2N_2Te_2$ requires C, 43.82; H, 4.73; N, 3.65%); $[\alpha]_D^{25}$ +620 (*c* 1.00, $CHCl_3$).

Asymmetric ring opening of *meso*-epoxides using chiral diferrocenyl dichalcogenides and $LiAlH_4$ (Schemes 2 and 3)

A typical experimental procedure using $(Fc*Se)_2$ is as follows. In a two-necked 50 cm^3 round-bottomed flask containing a magnetic stirring bar were placed $(Fc*Se)_2$ (155 mg, 0.21 mmol) and $LiAlH_4$ (16 mg, 0.42 mmol) under N_2. Dry THF (2 cm^3) was added to the flask at 0 °C, and the mixture became homogeneous after being stirred at 25 °C for 0.5 h. A dry THF (2 cm^3) solution of cyclohexene oxide (45 mg, 0.46 mmol) was then slowly added to the resulting solution and the mixture was stirred at 25 °C for 20 h. The completion of the reaction was examined by GLC. The mixture was treated with brine (200 cm^3) and then extracted with CH_2Cl_2 (50 cm^3 × 3). The combined extracts were dried over K_2CO_3 and evaporated to leave an orange oil which was purified by column chromatography on alumina with hexane–ethyl acetate (9:1) as eluent to give a diastereoisomeric mixture of trans-[(S,R)-2-(1-*dimethylaminoethyl)ferrocenyl] 2-hydroxycyclohexyl selenides* **5** (E = Se); [143 mg, 0.35 mmol, 83% yield based on $(Fc*Se)_2$]; δ_H(major product) 4.05–4.50 (3 H, m, C_5H_3), 4.08 (5 H, s, C_5H_5), 4.08 (1 H, q, *J* 6.75, $CHCH_3$), 3.48 (1 H, m, cyclohexyl-CH), 2.68 (1 H, m, cyclohexyl-CH), 2.18 [6 H, s, $N(CH_3)_2$], 1.9 (1 H, br, OH), 1.1–1.7 (8 H, m, cyclohexyl-CH_2) and 1.29 (3 H, d, *J* 6.75, $CHCH_3$); δ_H(minor product) 4.11 (5 H, s, C_5H_5), 2.16 [6 H, s, $N(CH_3)_2$] and 1.31 (3 H, d, *J* 6.75, $CHCH_3$); δ_C 92.8, 91.1, 77.2, 76.9, 73.9, 70.3, 70.0, 68.8, 68.7, 68.4, 68.2, 67.0, 56.8, 55.6, 52.6, 38.9, 36.0, 35.7, 35.4, 34.9, 32.6, 32.5, 27.3, 27.0, 25.1, 24.9 and 8.10. Elemental analysis of a diastereoisomeric mixture (Found: C, 55.3; H, 6.7; N, 3.2. $C_{20}H_{29}FeNOSe$ requires C, 55.32; H, 6.73; N, 3.23%).

The physical and spectroscopic data of other ring-opened products **5**–**8**, which were also obtained as diastereoisomeric mixtures, are as follows.

***trans*-[(*S*,*R*)-2-(1-Dimethylaminoethyl)ferrocenyl] 2-hydroxycyclohexyl sulfides 5 (E = S).** An orange oil; δ_H(major product) 4.03–4.52 (3 H, m, C_5H_3), 4.12 (1 H, q, *J* 6.75, $CHCH_3$), 4.11 (5 H, s, C_5H_5), 3.72 (1 H, m, cyclohexyl-CH), 2.68 (1 H, m, cyclohexyl-CH), 2.15 [6 H, s, $N(CH_3)_2$], 1.8 (1 H, br, OH), 1.2–1.9 (8 H, m, cyclohexyl-CH_2) and 1.29 (3 H, d, *J* 6.75, $CHCH_3$); δ_H(minor product) 4.13 (5 H, s, C_5H_5), 2.11 [6 H, s, $N(CH_3)_2$] and 1.31 (3 H, d, *J* 6.75, $CHCH_3$); δ_C 77.2, 76.8, 75.7, 70.5, 68.4, 68.2, 68.0, 66.9, 60.1, 56.2, 56.0, 56.0, 39.1, 38.9, 35.0, 34.9, 32.6, 29.7, 29.3, 26.8, 26.6, 25.1, 24.8 and 8.1. Elemental analysis of a diastereoisomeric mixture (Found: C, 62.4; H, 7.75; N, 3.3. $C_{20}H_{29}FeNOS$ requires C, 62.01; H, 7.55; N, 3.62%).

***trans*-[(*S*,*R*)-2-(1-Dimethylaminoethyl)ferrocenyl] 2-hydroxycyclohexyl tellurides 5 (E = Te).** An orange oil; δ_H(major product) 4.13–4.53 (3 H, m, C_5H_3), 4.09 (5 H, s, C_5H_5), 3.98 (1 H, q, *J* 6.75, $CHCH_3$), 3.04 (1 H, m, cyclohexyl-CH), 2.65 (1 H, m, cyclohexyl-CH), 2.18 [6 H, s, $N(CH_3)_2$], 1.9 (1 H, br, OH), 1.1–1.7 (8 H, m, cyclohexyl-CH_2) and 1.29 (3 H, d, *J* 6.75, $CHCH_3$); δ_H(minor product) 4.13 (5 H, s, C_5H_5), 2.16 [6 H, s, $N(CH_3)_2$] and 1.31 (3 H, d, *J* 6.75, $CHCH_3$); δ_C 95.2, 81.1, 80.8, 78.1, 77.2, 71.2, 70.1, 69.9, 69.8, 68.6, 67.5, 58.6, 45.3, 40.5, 40.5, 39.9, 39.1, 39.0, 38.2, 36.3, 34.6, 33.5, 29.7, 29.4, 27.7, 25.4, 25.2, 8.2 and 8.1. Elemental analysis of a diastereoisomeric mixture (Found: C, 49.9; H, 6.4; N, 3.1. $C_{20}H_{29}FeNOTe$ requires C, 49.75; H, 6.05; N, 2.90%).

***trans*-[(*S*,*R*)-2-(1-Dimethylaminoethyl)ferrocenyl] 2-hydroxycyclopentyl sulfides 6 (E = S).** An orange oil; δ_H(major product) 4.10–4.53 (3 H, m, C_5H_3), 4.11 (5 H, s, C_5H_5), 3.85 (1 H, q, *J* 6.75, $CHCH_3$), 3.15 (1 H, m, cyclopentyl-CH), 2.65 (1 H, m, cyclopentyl-CH), 2.22 [6 H, s, $N(CH_3)_2$], 1.6 (1 H, br, OH), 1.4–2.1 (6 H, m, cyclopentyl-CH_2) and 1.34 (3 H, d, *J* 6.75, $CHCH_3$); δ_H(minor product) 4.13 (5 H, s, C_5H_5), 2.18 [6 H, s, $N(CH_3)_2$] and 1.46 (3 H, d, *J* 6.75, $CHCH_3$); δ_C 92.7, 91.5, 82.0, 76.3, 76.2, 71.9, 70.4, 70.2, 68.9, 68.2, 68.1, 67.4, 66.9, 59.2, 55.5, 54.4, 40.4, 39.0, 32.1, 31.3, 30.5, 29.5, 29.2, 19.5, 19.2, 8.6 and 8.4. Elemental analysis of a diastereoisomeric mixture (Found: C, 61.3; H, 7.3; N, 3.7. $C_{19}H_{27}FeNOS$ requires C, 61.13; H, 7.29; N, 3.75%).

***trans*-[(*S*,*R*)-2-(1-Dimethylaminoethyl)ferrocenyl] 2-hydroxycyclopentyl selenides 6 (E = Se).** An orange oil; δ_H(major product) 4.00–4.55 (3 H, m, C_5H_3), 4.09 (5 H, s, C_5H_5), 4.04 (1 H, q, *J* 6.75, $CHCH_3$), 3.28 (1 H, m, cyclopentyl-CH), 2.74 (1 H, m, cyclopentyl-CH), 2.21 [6 H, s, $N(CH_3)_2$], 1.6 (1 H, br, OH), 1.2–1.9 (6 H, m, cyclopentyl-CH_2) and 1.33 (3 H, d, *J* 6.75, $CHCH_3$); δ_H(minor product) 4.13 (5 H, s, C_5H_5), 2.17 [6 H, s, $N(CH_3)_2$] and 1.35 (3 H, d, *J* 6.75, $CHCH_3$); δ_C 93.5, 82.5, 77.6, 77.2, 73.2, 70.3, 70.2, 70.1, 70.0, 69.0, 69.0, 68.5, 67.9, 67.5, 56.5, 56.5, 53.3, 49.0, 41.1, 39.1, 39.1, 32.3, 32.3, 30.4, 29.5, 20.3, 8.6 and 8.5. Elemental analysis of a diastereoisomeric mixture (Found: C, 53.9; H, 6.5; N, 3.1. $C_{19}H_{27}FeNOSe$ requires C, 54.31; H, 6.48; N, 3.30%).

***trans*-[(*S*,*R*)-2-(1-Dimethylaminoethyl)ferrocenyl] 2-hydroxycyclopentyl tellurides 6 (E = Te).** An orange oil; δ_H(major product) 4.15–4.51 (3 H, m, C_5H_3), 4.10 (5 H, s, C_5H_5), 4.00 (1 H, q, *J* 6.75, $CHCH_3$), 3.25 (1 H, m, cyclopentyl-CH), 2.86 (1 H, m, cyclopentyl-CH), 2.17 [6 H, s, $N(CH_3)_2$], 1.7 (1 H, br, OH), 1.3–1.9 (6 H, m, cyclopentyl-CH_2) and 1.33 (3 H, d, *J* 6.75, $CHCH_3$); δ_H(minor product) 4.11 (5 H, s, C_5H_5), 2.05 [6 H, s, $N(CH_3)_2$] and 1.45 (3 H, d, *J* 6.75, $CHCH_3$); δ_C 95.9, 95.3, 84.3, 81.3, 80.7, 75.2, 71.3, 71.2, 70.0, 69.8, 68.6, 67.8, 67.2, 58.5, 40.6, 39.2, 39.1, 35.5, 35.0, 32.9, 32.9, 30.6, 30.5, 22.4, 21.7, 16.1 and 8.5. Elemental analysis of a diastereoisomeric mixture (Found: C, 48.6; H, 5.8; N, 3.2. $C_{19}H_{27}FeNOTe$ requires C, 48.67; H, 5.80; N, 2.99%).

***trans*-[(*S*,*R*)-2-(1-Dimethylaminoethyl)ferrocenyl] 2-hydroxycyclooctyl sulfides 7 (E = S).** An orange oil; δ_H(major product) 4.1–4.5 (3 H, m, C_5H_3), 4.10 (5 H, s, C_5H_5), 3.86 (1 H, q, *J* 6.75, $CHCH_3$), 3.13 (1 H, m, cyclooctyl-CH), 2.60 (1 H, m, cyclooctyl-CH), 2.21 [6 H, s, $N(CH_3)_2$], 1.6 (1 H, br, OH), 1.0–2.0 (12 H, m, cyclooctyl-CH_2) and 1.31 (3 H, d, *J* 6.75, $CHCH_3$); δ_C 92.1, 91.0, 82.5, 76.5, 75.6, 71.4, 70.0, 70.0, 69.5, 68.5, 68.4, 67.6, 66.9, 58.2, 53.5, 52.1, 41.2, 38.5, 33.3, 30.2, 30.0, 28.5, 28.1, 18.9, 18.5, 8.4 and 8.4. Elemental analysis of a diastereoisomeric mixture (Found: C, 63.5; H, 7.8; N, 3.2. $C_{22}H_{33}FeNOS$ requires C, 63.61; H, 8.01; N, 3.37%).

‡ For details of the deposition scheme, see 'Instructions for Authors', *J. Chem. Soc., Perkin Trans. 1*, 1995, Issue 1.

***trans*-[(*S*,*R*)-2-(1-Dimethylaminoethyl)ferrocenyl] 2-hydroxycyclooctyl selenides 7 (E = Se).** An orange oil; δ_H(major product) 4.0–4.5 (3 H, m, C_5H_3), 4.09 (5 H, s, C_5H_5), 4.08 (1 H, q, *J* 6.75, $CHCH_3$), 3.48 (1 H, m, cyclooctyl-CH), 2.68 (1 H, m, cyclooctyl-CH), 2.18 [6 H, s, $N(CH_3)_2$], 1.9 (1 H, br, OH), 1.0–1.8 (12 H, m, cyclooctyl-CH_2) and 1.28 (3 H, d, *J* 6.75, $CHCH_3$); δ_C 92.7, 91.0, 77.1, 76.6, 73.2, 70.0, 69.5, 68.5, 68.2, 68.0, 68.0, 67.6, 56.5, 55.2, 52.2, 38.2, 36.9, 35.2, 35.1, 34.6, 32.4, 32.1, 27.9, 27.5, 25.2, 23.2 and 8.5. Elemental analysis of a diastereoisomeric mixture (Found: C, 57.0; H, 7.0; N, 2.75. $C_{22}H_{33}FeNOSe$ requires C, 57.16; H, 7.19; N, 3.03%).

***trans*-[(*S*,*R*)-2-(1-Dimethylaminoethyl)ferrocenyl] 2-hydroxycyclooctyl tellurides 7 (E = Te).** An orange oil; δ_H(major product) 4.1–4.5 (3 H, m, C_5H_3), 4.11 (5 H, s, C_5H_5), 4.10 (1 H, q, *J* 6.75, $CHCH_3$), 3.20 (1 H, m, cyclooctyl-CH), 2.95 (1 H, m, cyclooctyl-CH), 2.15 [6 H, s, $N(CH_3)_2$], 1.7 (1 H, br, OH), 1.0–1.8 (12 H, m, cyclooctyl-CH_2) and 1.30 (3 H, d, *J* 6.75, $CHCH_3$); δ_C 97.8, 94.2, 83.3, 80.9, 80.5, 74.2, 72.5, 72.5, 71.5, 69.5, 68.5, 67.5, 67.2, 57.2, 40.1, 39.0, 38.9, 34.9, 34.5, 31.5, 31.2, 30.4, 30.1, 21.9, 21.5, 15.9 and 8.4. Elemental analysis of a diastereoisomeric mixture (Found: C, 51.4; H, 6.55; N, 2.5. $C_{22}H_{33}FeNOTe$ requires C, 51.72; H, 6.51; N, 2.74%).

***trans*-[(*S*,*R*)-2-(1-Dimethylaminoethyl)ferrocenyl] 2-hydroxy-1,2-diphenylethyl sulfides 8 (E = S).** An orange oil; δ_H(major product) 6.9–7.2 (10 H, m, 2 × C_6H_5), 4.95 (1 H, m, CH), 4.52 (1 H, d, *J* 9.76, CH), 3.85–4.55 (3 H, m, C_5H_3), 4.18 (1 H, q, *J* 6.75, $CHCH_3$), 3.94 (5 H, s, C_5H_5), 3.1 (1 H, br, OH), 2.25 [6 H, s, $N(CH_3)_2$] and 1.39 (3 H, d, *J* 6.75, $CHCH_3$); δ_H(minor product) 4.08 (5 H, s, C_5H_5), 2.30 [6 H, s, $N(CH_3)_2$] and 1.36 (3 H, d, *J* 6.75, $CHCH_3$); δ_C 143.8, 142.8, 142.7, 141.3, 129.5, 129.2, 128.5, 128.4, 128.0, 127.7, 127.6, 127.3, 126.8, 126.6, 125.9, 92.0, 89.0, 83.3, 81.6, 75.8, 75.4, 75.3, 72.2, 70.6, 70.4, 68.9, 68.8, 67.9, 61.1, 56.2, 56.2, 46.1, 39.3, 39.1, 8.4 and 8.2. Elemental analysis of a diastereoisomeric mixture (Found: C, 69.0; H, 6.65; N, 2.8. $C_{28}H_{31}FeNOS$ requires C, 69.28; H, 6.44; N, 2.89%).

***trans*-[(*S*,*R*)-2-(1-Dimethylaminoethyl)ferrocenyl] 2-hydroxy-1,2-diphenylethyl selenides 8 (E = Se).** An orange oil; δ_H(major product) 6.8–7.2 (10 H, m, 2 × C_6H_5), 5.98 (1 H, d, *J* 9.76, CH), 4.45 (1 H, d, *J* 9.76, C*H*), 3.85–4.50 (3 H, m, C_5H_3), 4.03 (1 H, q, *J* 6.75, $CHCH_3$), 3.94 (5 H, s, C_5H_5), 2.15 [6 H, s, $N(CH_3)_2$], 2.1 (1 H, br, OH) and 1.27 (3 H, d, *J* 6.75, $CHCH_3$); δ_H(minor product) 3.98 (5 H, s, C_5H_5), 2.19 [6 H, s, $N(CH_3)_2$] and 1.25 (3 H, d, *J* 6.75, $CHCH_3$); δ_C 143.0, 142.8, 142.5, 140.4, 128.5, 128.4, 128.0, 127.8, 127.7, 127.1, 127.0, 126.8, 126.7, 126.7, 126.3, 92.9, 91.4, 91.3, 77.6, 77.2, 77.1, 75.3, 72.8, 70.3, 70.1, 69.1, 68.9, 68.9, 68.8, 67.3, 60.6, 57.0, 56.9, 39.2, 39.1, 29.3 and 8.3. Elemental analysis of a diastereoisomeric mixture (Found: C, 63.1; H, 5.6; N, 2.3. $C_{28}H_{31}FeNOSe$ requires C, 63.17; H, 5.87; N, 2.63%).

***trans*-[(*S*,*R*)-2-(1-Dimethylaminoethyl)ferrocenyl] 2-hydroxy-1,2-diphenylethyl tellurides 8 (E = Te).** An orange oil; δ_H(major product) 7.2–7.4 (10 H, m, 2 × C_6H_5), 4.91 (1 H, m, CH), 4.13 (1 H, d, *J* 9.76, CH), 4.2–4.3 (3 H, m, C_5H_3), 4.15 (1 H, q, *J* 6.75, $CHCH_3$), 4.12 (5 H, s, C_5H_5), 3.0 (1 H, br, OH), 2.12 [6 H, s, $N(CH_3)_2$] and 1.46 (3 H, d, *J* 6.75, $CHCH_3$); δ_C 143.9, 138.1, 129.5, 128.5, 128.4, 127.6, 126.6, 125.9, 78.0, 77.2, 75.4, 69.5, 68.6, 67.5, 67.3, 66.9, 58.7, 46.1, 40.5, 29.7 and 16.1. Elemental analysis of a diastereoisomeric mixture (Found: C, 57.75; H, 5.8; N, 2.1. $C_{28}H_{31}FeNOTe$ requires C, 57.88; H, 5.38; N, 2.41%).

Benzoylation and oxidation of compound 5 (E = Se)

To a solution of (*S*,*R*)-2-(1-dimethylaminoethyl)ferrocenyl 2-hydroxycyclohexyl selenide (*S*,*R*)-**5** (E = Se) (401 mg, 0.92 mmol) in CH_2Cl_2 (4 cm^3) and pyridine (70 mg, 0.92 mmol) was added benzoyl chloride (130 mg, 0.92 mmol) in CH_2Cl_2 (1 cm^3). The reaction mixture was stirred at 0 °C for 12 h at the same temperature and then quenched with brine (2 cm^3). The organic compound was extracted with CH_2Cl_2 (10 cm^3 × 2) and the combined extracts were washed with aqueous sodium hydrogen carbonate (15 cm^3). Evaporation of the solvent left a benzoylated product (482 mg, 97%). To this compound in CH_2Cl_2 (2 cm^3) was added 30% aqueous H_2O_2 (19 mg) in CH_2Cl_2 (2 cm^3) at 0 °C and the resulting mixture was stirred at 0 °C for 20 h. The mixture was quenched with saturated aqueous ammonium chloride and extracted with CH_2Cl_2. The extract was washed with saturated aqueous sodium hydrogen carbonate and brine and dried over K_2CO_3. After removal of the solvent, chromatographic separation of the residue over silica gel (Wakogel C-200) using EtOAc–hexane (1:9) as eluent gave the cyclohex-2-enyl benzoate **9** (29 mg, 85%). The optical purity of the product was determined by HPLC (Daicel Chiralcel OB column) and the configuration of the product was determined by comparison with authentic samples derived from commercial (*R*)-cyclohex-2-enol and racemic cyclohex-2-enol.

Acknowledgements

We thank Dr Kouichi Ohe for helpful discussion. This work was supported partly by a grant from Nagase Science and Technology Foundation and a Grant-in-Aid for Scientific Research from the Ministry of Education, Science and Culture, Japan. The authors Y. N. and J. D. S. gratefully acknowledge a Fellowship of the Japan Society for the Promotion of Science for Japanese Junior Scientists and the Ministry of Education, Science and Culture, Japan for the award of a research fellowship, respectively.

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Paper 5/03509K
Received 1*st June* 1995
Accepted 19*th July* 1995