Preparation of chiral tricarbonyl arene thiol chromium and its application to asymmetric ring opening of *meso*-epoxides

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Optically active (*R*,*S*)- and (*S*,*R*)-tricarbonyl {2-[1-(*N*,*N*-dimethylamino)ethyl]benzenethiol}chromiums have been prepared in moderate yield by the regioselective lithiation of tricarbonyl [*N*,*N*-dimethyl-α(*R*)-phenylethylamine]chromium and subsequent reaction of the product with elemental sulfur. The structure of the (*R*,*S*)-benzenethiolchromium complex was fully characterized by X-ray crystallography. The chiral benzenethiolchromium complexes reacted with cyclopentene oxide, cyclohexene oxide, 1-methylcyclohexene oxide, cycloheptene oxide and cyclooctene oxide and, after oxidative removal of the chromium moiety, gave the corresponding *trans* β-hydroxyalkyl aryl sulfides in high yield with moderate diastereoselectivity. The reaction proceeded without additives and the diastereoselectivity was not affected by the addition of lanthanide(III) complexes which are known to promote the ring-opening of an epoxide with benzenethiol.

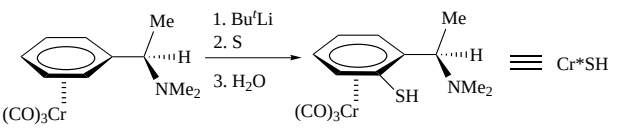
Introduction

Recently we have been interested in the preparation of chiral chalcogenide (sulfur, selenium, and tellurium) compounds for use in asymmetric organic synthesis. We have already prepared chiral diferrocenyl dichalcogenides and demonstrated that they are effective in achieving highly selective asymmetric organic syntheses: *e.g.*, selenoxide elimination,[1] a ligand of a rhodium catalyst for hydrosilylation,[2] a catalyst for ethylation with diethylzinc,[3] methoxyselenylation,[4] and the ring opening of *meso*-epoxides.[5] We have now prepared new chiral arenechromium complex-based sulfur compounds and applied them to the asymmetric ring opening of *meso*-epoxides. We here report the results of this study.

Results and discussion

Preparation of (*R*,*S*)- and (*S*,*R*)-tricarbonyl{2-[1-(*N*,*N*-dimethylamino)ethyl]benzenethiol}chromium 2

The highly diastereoselective *ortho* lithiation of tricarbonyl-[*N*,*N*-dimethyl-α(*R*)-phenylethylamine]chromium **1a** with Bu^{t}Li followed by the addition of sulfur afforded a single diastereoisomer of tricarbonyl{2-[1-(*N*,*N*-dimethylamino)-ethyl]benzenethiol}chromium **2a**. Its stereochemistry was determined to be *R*,*S*-configurated according to the literature (Scheme 1).[6] Similarly, starting from the enantiomer of **1a**, *i.e.*,



1a **2a** : (*R*,*S*)-Cr*SH

Scheme 1

the *S* isomer, the corresponding diastereoisomerically pure (*S*,*R*)-benzenethiolchromium complex **2b** was prepared in moderate yield (46%). In contrast, the chiral *N*,*N*-1-dimethylaminoethylferrocene-based sulfur compounds can be isolated as disulfides,[5] and the arenechromium-based sulfur compounds can be isolated as thiols. We refer to these compounds in an abbreviated form as (*R*,*S*)- and (*S*,*R*)-Cr*SH, respectively. The structure of **2a** was fully characterized by X-ray crystallography, and its absolute configuration was confirmed to be *R*,*S*, where the configuration around the benzene ring is *S* (Fig. 1). Selected bond distances and angles for **2a** are presented in Table 1.

Table 1 Selected bond distance and bond angles for **2a**

Bond distance (Å)			
S–C(1)	1.728(6)	C(1)–C(2)	1.447(8)
C(1)–C(6)	1.402(9)	C(2)–C(3)	1.404(8)
C(2)–C(7)	1.518(8)	C(3)–C(4)	1.396(9)
C(4)–C(5)	1.37(1)	C(5)–C(6)	1.40(1)
Cr–C(1)	2.351(6)	Cr–C(2)	2.243(5)
Cr–C(3)	2.209(6)	Cr–C(4)	2.226(7)
Cr–C(5)	2.222(8)	Cr–C(6)	2.250(7)
Cr–C(11)	1.827(8)	C(11)–O(1)	1.151(8)
Cr–C(12)	1.828(8)	C(12)–O(2)	1.145(9)
Cr–C(13)	1.816(6)	C(13)–O(3)	1.153(7)
Bond angle (°)			
S–C(1)–C(2)	122.5(5)	S–C(1)–C(6)	120.5(5)
C(2)–C(7)–C(8)	116.0(6)	N–C(7)–C(8)	111.4(6)
C(2)–C(7)–N	108.6(5)	C(7)–N–C(9)	112.8(5)
C(7)–N–C(10)	113.0(7)	C(9)–N–C(10)	109.7(7)

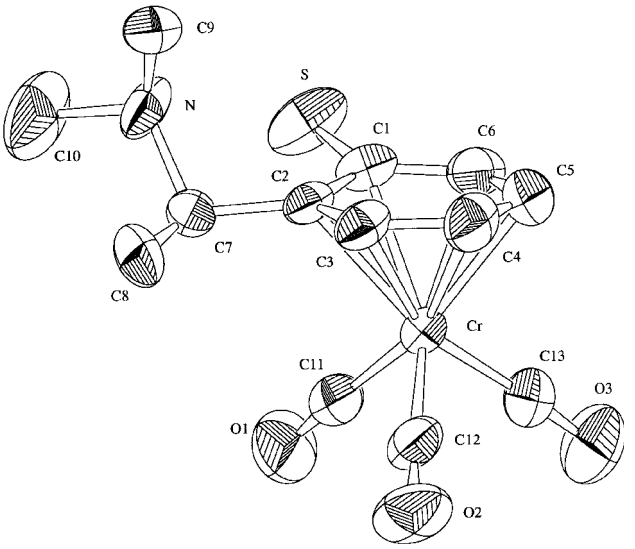


Fig. 1 ORTEP view of the complex **2a** (50% probability)

Table 2 Asymmetric ring opening of cyclohexene oxide with Cr*SH[a]

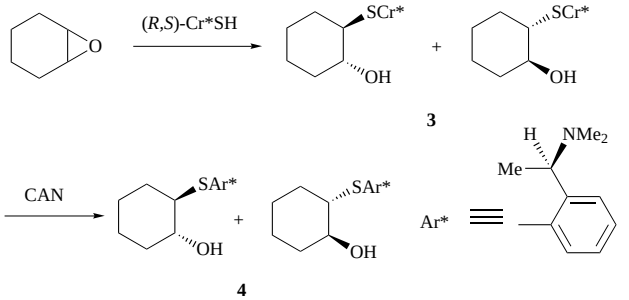
Run	Config'n of Cr*SH	Additive (20 mol%)	Solvent	Time (h)	Yield (%)[b]	De (%)[c]
1	*R*,*S*	None	CH_2Cl_2	20	44	25
2		None	CH_2Cl_2	40	68	39
3		None	CH_2Cl_2	65	93	34
4		$Eu(fod)_3$	CH_2Cl_2	65	93	40
5		$Eu(hfc)_3$	CH_2Cl_2	65	95	37
6		$Yb(hfc)_3$	CH_2Cl_2	65	94	41
7		$Yb(OTf)_3$	CH_2Cl_2	65	70	44
8		Et_3N[d]	CH_2Cl_2	65	39	30
9		None	MeCN	65	64	30
10		None	THF	65	93	40
11		None	Toluene	65	73	32
12	*S*,*R*	None	CH_2Cl_2	65	95	32
13		$Eu(hfc)_3$	CH_2Cl_2	65	95	22
14		$Yb(hfc)_3$	CH_2Cl_2	65	67	30

[a] The reaction was carried out at room temperature using Cr*SH (0.50 mmol), cyclohexene oxide (0.60 mmol), and an additive (0.10 mmol) in a solvent (20 ml). [b] Determined by GC. [c] Determined by ^{1}H NMR and/or HPLC using a Daicel Chiralcel OD column. [d] 0.5 mmol of Et_3N was added.

Complex **2a** exhibited the expected three-legged piano-stool structure and a staggered conformation with respect to the bonding between the η^6-arene and $Cr(CO)_3$ moieties. The Cr–C(1) distance {2.351(6) Å} is significantly longer than those of the other five (av. 2.23 Å) and the C(1)–C(2) distance {1.447(8) Å} is slightly longer than those of other five (av. 1.40 Å). Thus, the thiol sulfur and the *ipso*-carbon [C(1)] are significantly bent away from the $Cr(CO)_3$ fragment [deviation from the plane defined by C(3), C(4), C(5), C(6): S, 0.285 and C(1), 0.075 Å] while the $CHMeNMe_2$ carbon C(7) and the *ipso*-carbon [C(2)] are slightly bent toward the $Cr(CO)_3$ [C(7), −0.126 and C(2), −0.030]. A comparable degree of distortion has been observed in $[1,4\text{-}C_6H_4Bu^t_2]Cr(CO)_2PPh_3$.[7] We assume that the structure **2a** largely arises from steric hindrance between the substituents and $Cr(CO)_3$ moiety, although Hunter *et al.* discussed in detail the distortions in the arene planarity of the (η^6-arene)$Cr(CO)_3$ complexes based on the electronic effects of the substituents on the arene.[8]

Asymmetric ring-opening of *meso*-epoxides with the chiral benzenethiolchromium complex, Cr*SH[9]

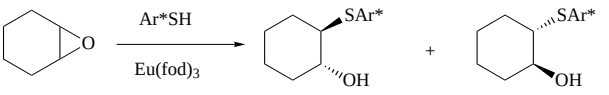
The reaction of (*R*,*S*)-Cr*SH **2a** with cyclohexene oxide in CH_2Cl_2 at room temperature followed by oxidation with ceric ammonium nitrate (CAN) gave a diastereoisomeric mixture of the corresponding *trans*-(*R*,*S*)-2-(1-*N*,*N*-dimethylaminoethyl)-phenyl 2-hydroxycyclohexyl sulfide **4** in a high yield (93%) but with moderate selectivity (40% de) (Scheme 2). The diastereo-



Scheme 2

isomeric excess (de) was determined by ^{1}H NMR integration of the methine proton of the amino group and/or HPLC using a Daicel Chiralcel OD column. In contrast to the ring opening of epoxides with benzenethiol which requires a Lewis acid catalysis,[9,10] whereas the reaction with Cr*SH proceeded without additives. However, the ring-opening reaction is slow and requires a long reaction time (65 h). When the reaction was carried out for shorter periods of time, *i.e.*, 20 or 40 h, the yield remarkably decreased (20 h) or was not satisfactory (40 h). In an attempt to improve the de value, the reaction was carried out in the presence of various additives. The results are summarized in Table 2. Since Vougioukas and Kagan reported that trivalent lanthanide compounds effectively catalyze the ring opening of an epoxide with benzenethiol, some lanthanide compounds were screened as additives.[10] The addition of $SmCl_3$ spoiled the reaction since it reacted itself with cyclohexene oxide to give 1-chlorohexan-2-ol. The addition of $Yb(OTf)_3$ or $Eu(fod)_3$ showed no notable effect on the reaction. A chiral lanthanide reagent such as (−)-$Eu(hfc)_3$, and (−)-$Yb(hfc)_3$ did not significantly affect the de value obtained from the reaction with either diastereoisomer of (*R*,*S*)-Cr*SH **2a** or (*S*,*R*)-Cr*SH **2b**. The addition of triethylamine gave a decrease in the yield and selectivity. The yield and selectivity of the ring-opened product was not affected by solvent; similar yields and selectivities were obtained when THF and toluene were used as solvents.

To evaluate the influences of the tricarbonylchromium moiety, the ring-opening reaction of the cyclohexene oxide was carried out using chromium-free arenethiol, *i.e.*, (*R*)-2-[1-(*N*,*N*-dimethylamino)ethyl]benzenethiol[11] in the presence of $Eu(fod)_3$. The ring-opened product **4** was obtained with lower selectivity (13% de) and a moderate yield (41%) (Scheme 3). The electron-withdrawing tricarbonylchromium moiety



Scheme 3

activates the nucleophilicity of the thiol group and the configuration around the benzene ring is essential for the diastereoselective nucleophilic reaction.

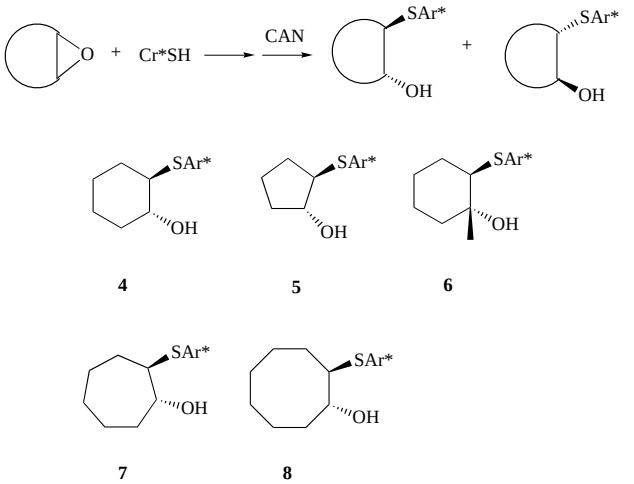
The ring opening of various epoxides was carried out with **2a** under specific conditions, *i.e.*, at room temperature for 65 h in CH_2Cl_2 (Scheme 4). The results are shown in Table 3. The selectivity with each epoxide was low (20–30% de) and the chemical yield of the ring-opened product was moderate (44–69%).

The configuration of the ring-opened product **4** was confirmed by sulfoxide elimination of the benzoate ester of β-hydroxy sulfide **9** (Scheme 5).[9,12] Thus, the oxidation of the diastereoisomeric mixture of **9** (40% de) by *m*-chloroperbenzoic acid occurred when the compound was refluxed in toluene to give cyclohex-2-enyl benzoate **10** (53%). The enantiomeric excess was determined by HPLC (Daisel Chiralcel OB column) and the configuration of the product was determined by

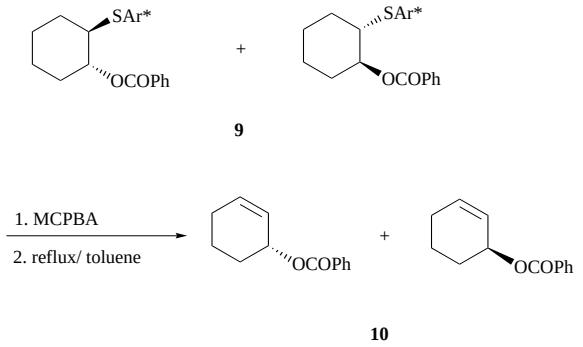
Table 3 Asymmetric ring opening reaction of *meso*-epoxides with (*R*,*S*)-Cr*SH[a]

Run	Epoxide	Product	Yield (%)[b]	De(%)[c]
1	Cyclopentene oxide	**5**	65	20
2	1-Methylcyclohexene oxide	**6**	44	23
3	Cycloheptene oxide	**7**	69	29
4	Cyclooctene oxide	**8**	65	22

[a] The reaction was carried out at room temperature for 65 h in CH_2Cl_2 using (*R*,*S*)-Cr*SH (0.50 mmol) and epoxide (0.60 mmol). [b] Determined by GC. [c] Determined by ^{1}H NMR and/or HPLC using a Daicel Chiralcel OD column.



Scheme 4



Scheme 5

comparison with authentic samples.[5] The (*R*)-**10** was formed in 40% ee from (*R*,*S*)-Cr*SH. The determined enantiomeric excess was consistent with the diastereoisomer excess of **4**.

Experimental

General

^{1}H and ^{13}C NMR spectra were recorded on a JEOL JNM A-400 NMR (400 MHz) spectrometer as solutions in $CDCl_3$. The chemical shifts are reported in δ units downfield from the internal reference, Me_4Si. *J* Values are given in Hz. IR spectra were obtained with a JASCO Herschel FT/IR-230A spectrometer. HPLC analyses were carried out on a Hitachi L-6200 apparatus equipped with a UV detector using Daicel Chiralcel OB and OD columns (0.46 mm, 25 cm) eluting with propan-2-ol–hexane (1:9). Elemental analyses were carried out using a Yanaco CHN CORDER MT-5. Preparative TLC was conducted using a 20 × 20 cm glass sheet coated with a 2-mm thick layer of Merck Kieselgel 60 PF_{254}. [*a*] Values are recorded as 10^{-1} deg cm^2 g^{-1}.

Materials

Hexacarbonylchromium was purchased from Strem Chemicals, Inc. Chromium complexes **1a** and **1b** were prepared according to the literature method.[6] Sulfur was purified by sublimation before use. Epoxides were prepared by oxidation of the corresponding alkenes with *m*-chloroperbenzoic acid. Bu^{t}Li was purchased from Kanto Chemicals (Japan) Co., Ltd and used after titration.

Preparation of (*R*,*S*)-tricarbonyl{2-[1-(*N*,*N*-dimethylamino)-ethyl]benzenethiol}chromium (Cr*SH) 2a

A 50-cm^3 three-neck round-bottom flask containing a magnetic stirring bar was charged with tricarbonyl[*N*,*N*-dimethyl-α(*R*)-phenylethylamine]chromium **1a** (105 mg, 3.7 mmol) under nitrogen. Dry diethyl ether (30 cm^3) was added to the flask followed by a hexane solution of Bu^{t}Li (1.6 M; 2.7 cm^3, 4.40 mmol) using a syringe through a rubber septum at −40 °C over a period of 15 min. After the addition of dry THF (4.6 cm^3), the resulting solution was stirred at −40 °C for 1 h. Sulfur powder (141 mg, 4.4 mmol) was then added portionwise to the mixture at the same temperature. The resulting mixture was allowed to warm to −10 °C at which temperature it was stirred for 3 h; subsequently it was stirred at room temperature for an additional 17 h. After this, the mixture was poured into water and unchanged **1a** extracted with diethyl ether. The water layer was adjusted to pH 7 with dilute aq. HCl and then extracted with $CHCl_3$ (20 cm^3 × 3). The combined extracts were washed with brine, dried (K_2CO_3) and evaporated to afford crude **2a** (513 mg, 44%) as a yellow solid which was recrystallized from hexane–CH_2Cl_2 (Found: C, 49.20; H, 4.70; N, 4.41. Calc. for $C_{13}H_{15}NO_3SCr$: C, 49.20; H, 4.76; N, 4.41%); mp 116 °C (decomp.) (from hexane); ν_{max}(KBr)/cm^{-1} 2972, 2828, 1958 and 1877; δ_H 1.58 (3 H, d, *J* 7.0 CHCH_3), 2.67 [6 H, s, N(CH_3)$_2$] and 4.6–5.6 (6 H, m, Ph and C*H*); δ_C 7.4, 36.9, 64.0, 84.2, 93.5, 96.7, 98.7 and 139.9; $[a]_D^{25}$ −256.3 (*c* 0.515 in $CHCl_3$).

(*S*,*R*)-Tricarbonyl{2-[1-(*N*,*N*-dimethylamino)ethyl]benzenethiol}chromium 2b

The title compound was similarly prepared from [*N*,*N*-dimethyl-α(*S*)-phenylethylamine]chromium (536 mg, 46%) as a yellow solid (Found: C, 49.30; H, 4.60; N, 4.31. Calc. for $C_{13}H_{15}NO_3SCr$: C, 49.20; H, 4.76; N, 4.41%); mp 116 °C (decomp.) (from hexane); $[a]_D^{25}$ 128.71 (*c* 0.213 in $CHCl_3$).

Asymmetric ring-opening of *meso*-epoxides

The following is a typical experimental procedure for the asymmetric ring-opening of *meso*-epoxides. A 20-cm^3 two-neck round-bottom flask containing a magnetic stirring bar was charged with **2a** (159 mg, 0.50 mmol) and (−)-Eu(hfc)$_3$ (119 mg, 0.10 mmol) under nitrogen. A CH_2Cl_2 (2.5 cm^3) solution of cyclohexene oxide (60 mg, 0.60 mmol) was added to the flask and the resulting mixture was stirred at room temperature for 65 h with shielding from the light. The completion of the reaction was checked by TLC. After concentration of the mixture by evaporation of the solvent, the residue was treated with a methanol solution (25 cm^3) of CAN (2.74 g, 5.0 mmol) and K_2CO_3 in order to remove the chromium moiety. The mixture was stirred at room temperature for 1 h after which insoluble material was filtered off. The filtrate was poured into water and the pH of the solution was adjusted to *ca.* 7 with aqueous $NaHCO_3$. The solution was extracted with ethyl acetate (10 cm^3 × 3) and the combined extracts were dried (K_2CO_3) and evaporated to afford a yellow oil. This was purified by preparative TLC on neutral alumina with hexane–ethyl acetate (4:1) as the eluent to give a diastereoisomeric mixture of *trans*-[(*R*,*S*)-2-(1-*N*,*N*-dimethylaminoethyl)phenyl] 2-hydroxycyclohexyl sulfide **4** as a pale yellow oil (133 mg, 0.48 mmol, 95% based on Cr*SH) (Found: C, 68.70; H, 8.96; N, 4.71. Calc. for $C_{16}H_{25}NOS$: C, 68.77; H, 9.02; N, 5.01%); ν_{max}(KBr)/cm^{-1} 3393, 2933, 1447, 1357, 1080 and 755; δ_H(major diastereoisomer) 1.31 (3 H, d, *J* 6.9, NCHCH_3), 1.4–1.7 (8 H, m, cyclohexyl), 2.26 [6 H, s, N(CH_3)$_2$], 2.85 (q, 1H, *J* 8.0, NC*H*CH$_3$), 3.45 (0.7 H, q, *J*

7.0, C*H*O), 4.66 (0.7 H, q, *J* 7.0, C*H*S) and 7.1–7.6 (4 H, m, 4H, Ph); δ_H(minor diastereoisomer, distinct signals) 3.07 (0.3 H, q, *J* 7.0, C*H*O) and 4.38 (0.3 H, q, *J* 7.0, C*H*S); δ_C(major diastereoisomer) 8.6, 24.5, 26.5, 33.2, 34.5, 39.4, 41.1, 58.5, 61.2, 70.7, 76.7, 126.5, 126.7, 127.5, 135.1, 137.8 and 142.8; δ_C(minor diastereoisomer) 26.6, 34.4, 57.4, 60.2, 126.8, 127.9, 132.8, 135.6 and 146.0.

***trans*-{(*R*,*S*)-2-[1-(*N*,*N*-Dimethylamino)ethyl]phenyl} 2-hydroxycyclopentyl sulfides 5**

The title compound, obtained as a mixture of diastereoisomers by the reaction of cyclopentene oxide with (*R*,*S*)-Cr*SH followed by treatment with CAN (86 mg, 65%), was a pale yellow oil (Found: C, 67.71; H, 8.82; N, 5.14; Calc. for $C_{15}H_{23}NOS$: C, 67.88; H, 8.73; N, 5.28%); ν_{max}(KBr)/cm^{-1} 3376, 2963, 2774, 1588, 1469, 1076 and 755; δ_H(major diastereoisomer) 1.22 (3 H, d, *J* 6.9, NCHC*H*$_3$), 1.5–1.9 (8 H, m, cyclopentyl) 2.20 [6 H, s, N(C*H*$_3$)$_2$], 2.98 (0.6 H, q, *J* 8.0, NC*H*CH$_3$), 3.59 (0.6 H, q, *J* 7.0, C*H*O), 4.63 (1 H, q, *J* 7.0, C*H*S) and 7.1–7.5 (4 H, m, Ph); δ_H(minor diastereoisomer, distinct signals) 3.07 (0.4 H, q, *J* 6.8, cyclopentyl) and 4.25 (0.4 H, q, *J* 7.0, C*H*S); δ_C(major diastereoisomer) 10.9, 20.0, 29.9, 31.7, 40.2, 54.4, 58.9, 76.0, 127.0, 127.1, 127.7, 133.7, 135.4 and 144.2; δ_C(minor diastereoisomer) 14,5, 21.0, 31.2, 32.2, 41.5, 58.7, 60.0, 81.0, 127.2, 128.0, 133.9, 136.6 and 145.4.

***trans*-{(*R*,*S*)-2-[1-(*N*,*N*-Dimethylamino)ethyl]phenyl} 2-hydroxy-2-methylcyclohexyl sulfides 6**

The title compound, obtained as a mixture of diastereoisomers by the reaction of 1-methylcyclohexene oxide with (*R*,*S*)-Cr*SH followed by treatment with CAN (64.6 mg, 44%), was a pale yellow oil (Found: C, 69.36; H, 9.27; N, 4.77. Calc. for $C_{17}H_{27}NOS$: C, 69.58; H, 9.27; N, 4.77%); ν_{max}(KBr)/cm^{-1} 3391, 2974, 2859, 1462, 1370 and 759; δ_H(major diastereoisomer) 1.2–1.3 (6 H, m, NCHC*H*$_3$ and C*H*$_3$), 1.4–1.8 (8 H, m, cyclohexyl), 2.15 [6 H, s, N(C*H*$_3$)$_2$], 2.96 (1 H, m, *J* 8.0, NC*H*CH$_3$), 4.56 (0.6 H, q, *J* 7.0, C*H*S) and 7.1–7.5 (4 H, m, Ph); δ_H(minor diastereoisomer, distinct signals) 3.80 (0.4 H, q, *J* 7.0, C*H*S); δ_C(major diastereomer) 9.0, 20.0, 23.2, 27.1, 33.7, 39.8, 43.5, 58.7, 66.2, 72.9, 127.2, 127.8, 128.1, 135.0, 139.0 and 143.1; δ_C(minor diastereoisomer) 21.6, 22.6, 26.2, 32.6, 39.9, 63.1, 72.6, 126.9, 127.3, 133.3 and 146.4.

***trans*-{(*R*,*S*)-2-[1-(*N*,*N*-Dimethylamino)ethyl]phenyl} 2-hydroxycycloheptyl sulfides 7**

The title compound, obtained as a mixture of diastereoisomers by the reaction of cycloheptene oxide with (*R*,*S*)-Cr*SH followed by treatment with CAN (99 mg, 69%), was a pale yellow oil (Found: C, 70.24; H, 9.46; N, 4.58; Calc. for $C_{18}H_{29}NOS$: C, 70.31; H, 9.51; N, 4.56); ν_{max}(KBr)/cm^{-1} 3358, 2946, 2804, 1432, 1025 and 748; δ_H(major diastereoisomer) 1.20 (3 H, d, *J* 6.8, NCHC*H*$_3$), 1.4–1.8 (10 H, m, cycloheptyl), 2.04 [6 H, s, N(C*H*$_3$)$_2$], 3.14 (1 H, q, *J* 8.0, NC*H*CH$_3$), 3.83 (0.65 H, q, *J* 7.0, C*H*O), 4.22 (0.65 H, q, *J* 7.0, C*H*S) and 7.0–7.6 (4 H, m, Ph); δ_H(minor diastereoisomers, distinct signals) 3.56 (0.35 H, q, *J* 7.0, C*H*O) and 4.18 (0.35 H, q, *J* 7.0, C*H*S); δ_C(major diastereoisomer) 10.9, 21.2, 22.3, 25.9, 27.3, 32.9, 40.3, 59.2, 63.0, 78.4, 126.8, 127.2, 127.8, 134.0, 137.6 and 143.1; δ_C(minor diastereoisomer) 26.6, 28.0, 34.3, 41.8, 60.8, 73.9, 126.9, 127.1, 127.3, 127.4 and 146.6.

***trans*-{(*R*,*S*)-2-[1-(*N*,*N*-Dimethylamino)ethyl]phenyl} 2-hydroxycyclooctyl sulfides 8**

The title compound, obtained as a mixture of diastereoisomers by the reaction of cyclooctene oxide with (*R*,*S*)-Cr*SH followed by treatment with CAN (101 mg, 65%), was a pale yellow oil (Found: C, 69.44; H, 9.34; N, 4.77. Calc. for $C_{17}H_{27}NOS$: C, 69.58; H, 9.27; N, 4.77%); ν_{max}(KBr)/cm^{-1} 3396, 2929, 2858, 1457, 1037 and 754; δ_H(major diastereoisomer) 1.22 (3 H, d, *J* 6.9, NCHC*H*$_3$), 1.3–1.8 (12 H, m, cyclooctyl), 2.16 [6 H, s, N(C*H*$_3$)$_2$], 3.02 (1 H, q, *J* 8.0, NC*H*CH$_3$), 3.78 (0.6 H, q, *J* 7.0, C*H*O), 5.21 (0.6 H, q, *J* 7.0, C*H*S) and 7.3–7.8 (4 H, m, Ph); δ_H(minor diastereoisomer, distinct signals) 3.56 (0.4 H, q, *J* 7.0, C*H*O) and 4.93 (0.4 H, q, *J* 7.0, C*H*S); δ_C(major diastereoisomer) 10.0, 22.3, 25.9, 27.1, 28.0, 32.1, 34.6, 40.3, 59.1, 63.1, 78.5, 126.7, 127.2, 127.8, 133.9, 136.1 and 143.1; δ_C(minor diastereoisomer) 21.2, 26.7, 27.7, 33.4, 34.4, 41.3, 59.5, 60.8, 74.9, 126.9, 127.1, 127.3, 127.5 and 146.6.

Benzoylation and oxidation of compound 4

To a pyridine (5 cm^3) solution of *trans*-[(*R*,*S*)-2-(1-dimethylaminoethyl)phenyl] 2-hydroxycyclohexyl sulfide **4** (552 mg, 1.98 mmol) was added benzoyl chloride (361 mg, 2.57 mmol). The reaction mixture was stirred at room temperature for 12 h and then quenched with water. The organic phase was extracted with diethyl ether (20 cm^3 × 3) and the combined extracts were washed with aq. $NaHCO_3$, dried (K_2CO_3) and evaporated to afford the benzoylated product **9** as a yellow oil. *m*-Chloroperbenzoic acid (80%, 232 mg, 1.34 mmol) was added to CH_2Cl_2 solution of compound **9** and the mixture was stirred at room temperature for 5 h. It was then quenched with water and extracted with diethyl ether (20 cm^3 × 3). The combined extracts were washed with aq. $NaHCO_3$ and dried (K_2CO_3). After evaporation of the solvent a toluene solution of the residue was stirred at reflux for 16 h and then allowed to cool to room temperature. Concentration of the mixture by evaporation of the solvent left **10** as a dark yellow oil which was subjected to preparative TLC on silica gel; hexane–EtOAc(5 : 1) eluted cyclohex-2-enyl benzoate. The optical purity of **10** was determined by HPLC using a Daicel Chiralcel OB column.

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

The unit-cell parameters were determined and the intensities were collected on a Rigaku AFC 7S four-circle diffractometer, with a graphite-monochromated Mo-Kα radiation (λ = 0.71069 Å}). Data for **2a** (a light-yellow crystal, grown in hexane), $C_{13}H_{15}NO_3SCr$, M = 317.32. Monoclinic, space group $P2_1$, α = 6.396(1), b = 11.393(2), c = 9.970(1) Å, β = 99.59(1)°, U = 716.3(2) Å^3, Z = 2, D_c = 1.471 g cm^{-3}, μ(Mo-Kα) = 9.46 cm^{-1}, crystal size 0.30 × 0.30 × 0.15 mm. The data were collected at a temperature of 296 ± 1 °C using the ω-2θ scan technique to a maximum 2θ value of 50.0°. Of the 1460 reflections which were collected, 1337 were unique (R_{int} = 0.021) and 1045 with $I \geqslant 3\sigma$ (I) were used in all calculations. The intensity of three representative reflections, measured after every 150 reflections, showed no significant decay. Azimuthal scans of several reflections indicated no need for an absorption correction. The data were corrected for Lorentz and polarization effects. The structure was solved using the heavy-atom method and refined by full-matrix least-square minimization of Σw $(|F_o| - |F_c|)^2$ with anisotropic thermal parameters for all the non-hydrogen atoms. It was not possible to locate the hydrogen atom attached to S in the Fourier difference map and it was not included in the refinement model; other hydrogen atoms were generated geometrically. They were assigned isotropic temperature factors and included in the structure-factor calculations but not refined. All calculations were performed using the TEXSAN package (ver 5.1) on a micro Indy computer. Final R = 0.034, R_w = 0.034, $\Delta\rho$ = +0.33 e Å^{-3}, −0.19 e Å^{-3}, maximum shift/error = 0.04. S = 0.72 for 171 parameters.

All the detailed crystallographic results have been deposited with the Cambridge Crystallographic Data Centre and are available on request.† Any such request should be accompanied by a full bibliographic citation for this work together with the reference number 207/135.

† For details of this Scheme, see Instructions for Authors (1997), *J. Chem. Soc.*, *Perkin Trans. 1*, 1997, Issue 1.

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