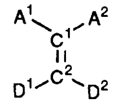
Enantiomer and Diastereoisomer Resolution, Rotational Barriers, and CD and UV Spectra of Some Twisted Push–Pull Ethylenes

Agha Zul-Qarnain Khan[a] **and Jan Sandström** *[,b]
[a] *PCSIR-FRC, Off University Road, Karachi-39, Pakistan*
[b] *Division of Organic Chemistry 1, Chemical Center, University of Lund, PO Box 124, S-221 00 Lund, Sweden*

Suitably substituted twisted push–pull ethylenes capable of existing either as mixtures of achiral diastereoisomers or as pairs of enantiomers have been resolved, in the first case into diastereoisomers by HPLC on silica, in the second case into enantiomers by chiral chromatography on tris(phenylcarbamoyl)cellulose. Free energy barriers to rotation through the planar state have been determined by monitoring respectively the rate of diastereoisomer interconversion and the rate of racemization at elevated temperatures. UV and CD spectra have been analysed with the aid of CNDO/S calculations for simplified models.

Push–pull ethylenes (**1**, A^1 and A^2 are acceptor groups, D^1 and D^2 are donor groups) with two alkylamino groups included in a five- or six-membered ring as donors tend to take up conformations, which are twisted about the C-1–C-2 bond.[1–4] When the acceptor part is the same, the degree of twisting is larger with a six-membered than with a five-membered ring.[5,6] In a recent work,[6] the twist angle Θ has been discussed in terms of the interplay between the strain energy, *i.e.* the repulsion between the donor and acceptor parts (E_{ster}), which opposes the planarity of the molecule, and the electronic energy (E_π, the energy of electronic interaction between the donor and acceptor parts), which stabilizes preferentially the planar state. The total energy of the molecule (E_{tot}) is the sum of these two contributions (Fig. 1), and the value of Θ depends on the shapes of the E_{ster} and E_π curves.



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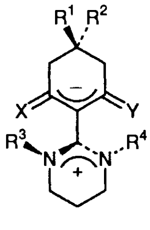
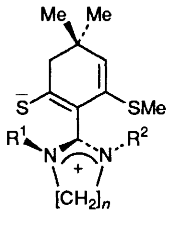


2a $R^1 = R^2 = Me$, $R^3 = R^4 = CH_2Ph$, X = Y = O
b $R^1 = R^2 = Me$, $R^3 = R^4 = CH_2Ph$, X = Y = S
c $R^1 = R^2 = Me$, $R^3 = Pr^i$, $R^4 = CH_2Ph$, X = O, Y = S
d $R^1 = R^2 = Me$, $R^3 = Pr^i$, $R^4 = CH_2Ph$, X = Y = S
e $R^1 = H$, $R^2 = Ph$, $R^3 = Pr^i$, $R^4 = CH_2Ph$, X = Y = O



3a $R^1 = R^2 = CH_2Ph$, $n = 3$
b $R^1 = Pr^i$, $R^2 = CH_2Ph$, $n = 2$
c $R^1 = Pr^i$, $R^2 = CH_2Ph$, $n = 3$

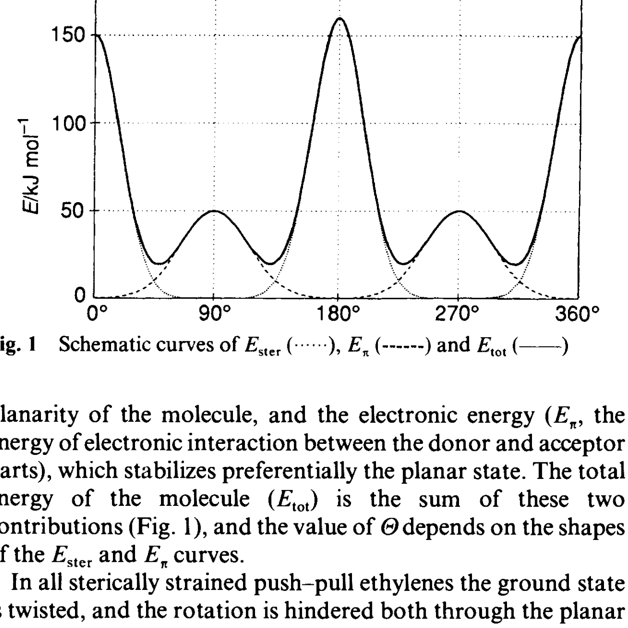


Fig. 1 Schematic curves of E_{ster} (⋯⋯), E_π (------) and E_{tot} (——)

In all sterically strained push–pull ethylenes the ground state is twisted, and the rotation is hindered both through the planar state and through the 90° twisted state. In the first case E_{tot} of the transition state is largely steric in origin, while in the second it can mainly be ascribed to loss of stabilizing π-electron energy. It follows from Fig. 1 that the twisted ground state has large contributions of both kinds of energy, and thus the rotational barrier in both cases depends on both E_{ster} and E_π.

Rotational barriers of both kinds, *i.e.* to passage through the planar state ('steric barrier') and to passage through the 90° twisted state ('π-electron barrier') have been measured by NMR bandshape technique (see ref. 3 and refs. quoted therein), in one case even in the same molecule.[7] However, in push–pull ethylenes, in which donor and/or acceptor groups are included in cyclic systems with concomitant strong steric interaction, the steric barrier may be too high (> 110 kJ mol^{-1}) to be measured by NMR technique within the accessible temperature range ($T < 200$ °C), while at the same time the π-electron barrier is too low (< 16 kJ mol^{-1}, $T < -140$ °C). These highly twisted compounds are better described as betaines composed of stabilized carbanions and carbocations than as ethylenes.

Strongly crowded push–pull ethylenes with different acceptor ($A^1 \neq A^2$) and different donor groups ($D^1 \neq D^2$) are chiral, and when the steric barrier is sufficiently high, they may be

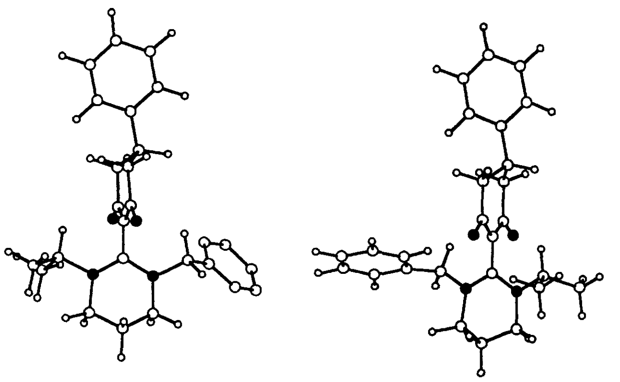


Fig. 2 Structures of the diastereoisomeric forms of **2e** based on crystal structures of three analogues (ref. 6) and on force-field calculations

Table 1 Rate constants and free energies of activation to rotation about the C-1–C-2 bond for compound **2e** (the A→B exchange at 89.0 °C in toluene) and for compounds **3b** and **3c** (racemization at 91 °C in hexane –propan-2-ol, 9 : 1)

Compd.	t/s	$[A]_t/10^{-3}$ mol dm^{-3}	$k_1/10^5$ s^{-1}	$\Delta G^‡$/ kJ mol^{-1}
2e	3 300	3.45	1.22	116.4
	6 900	2.80	1.16	116.6
	14 100	2.27	1.29	116.2
	∞	2.16	—	—
		Rel. ellipticity		
3b	0	1.00	—	—
	3 600	0.78	3.5	120.9
	7 200	0.63	3.2	121.1
	16 200	0.29	3.9	120.5
3c		0.97	0.42	127.2
	3 600	0.92	0.40	127.4
	10 800	0.72	0.48	126.9
	34 200			

resolved by chiral chromatography, *e.g.* on swollen microcrystalline triacetylcellulose (TAC). The thermal racemization of the enantiomers can be monitored with aid of the CD spectra, and in this way the rate of rotation through the planar state has been determined for several compounds, and free energy barriers in the range 112–126 kJ mol^{-1} have been measured.[8,9] The highest barrier (> 126.8 kJ mol^{-1})[9] was found for the oxo-thioxo compound **2c**.

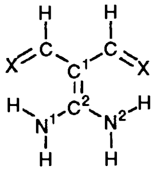
The barriers to rotation about the C-1–C-2 bond in compounds such as **2a**, **b**, **d** and **e** cannot be measured by racemization, since these molecules possess time-average planes of symmetry. However, **2e**, although achiral, can in the 90° twisted conformation exist in two diastereoisomeric forms, A and B (Fig. 2), which are interconverted by rotation about the C-1–C-2 bond. Synthesis of **2e** gave a solid, consisting according to NMR spectra of two forms in the ratio 1 : 1.8, which could be separated by HPLC. Thermal isomerization of one nearly pure isomer (A) in toluene at 89 °C followed by HPLC gave the barrier 116.4 ± 0.2 kJ mol^{-1} (A→B, Table 1). The 'sofa' conformation of the cyclohexane ring with an equatorial phenyl group follows from the values of the vicinal coupling constants J_{AX} and J_{BX}, one corresponding to an axial–axial and the other one to an axial–equatorial relation of the hydrogen atoms, as reported earlier for some analogous compounds.[10,11] Assignment of the forms A and B (first and second eluted isomer) to the isomeric structures in Fig. 2 has not been possible.

Comparison of the barriers for **2c** and **e**, > 126 and 116 kJ mol^{-1} respectively, leads to the conclusion that the barrier in the dithioxo compound **2d** is at least 130 kJ mol^{-1}. The dithioxo analogue of **2e** has also been prepared as a mixture of two diastereoisomers, but thermal isomerization without complete decomposition is not feasible.

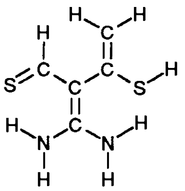
In a recent work[6] we have studied the crystal structures of the 2,6-dioxo and 2,6-dithioxo compounds **2a** and **b** and of 1,3-dibenzyl-2-[4,4-dimethyl-2-(methylthio)-6-thioxocyclohex-2-enylidene]hexahydropyrimidine (**3a**). The twist angle Θ between the donor and acceptor planes is 72.5° for **3a**, while for **2b** with rather similar steric conditions it is 85.1°. The lower Θ value for **3a** was ascribed to a higher $\Delta E_\pi(90)$ value. It follows from Fig. 1 that increasing E_π with constant E_{ster} should lead to a diminished Θ and a lowering of the steric barrier. In order to test this assumption concerning the barrier, we have resolved the chiral analogues **3b** and **c** by chiral chromatography and determined the free energy barriers to rotation by thermal racemization at *ca.* 90 °C. The barriers were found to be 121 ± 0.5 and 127 ± 0.5 kJ mol^{-1} respectively (Table 1), and the difference illustrates the effect of the ring size, the five-membered donor ring in **3b** giving a smaller steric effect than the six-membered one in **3c**. The barrier for **3c** is clearly lower than that estimated for **2d**, as required by the arguments above.

UV and CD Spectra.—The near-UV spectra of compounds **2a**, **b** and **3a** have been recorded in methylene dichloride–cyclohexane and in ethanol solution (Table 2). The absorption of the benzyl substituents is weak in the wavelength region discussed below and will not influence the conclusions.

In the spectra of **2a** and **b** one could expect weak n→π* and strong π→π* transitions. Both types of transitions should fall at considerably longer wavelengths for the thiocarbonyl compound **2b** than for the oxygen analogue **2a**. Then n→π* transitions, like all transitions originating in the oxygen or sulfur lone pair orbitals, should undergo strong blue-shifts when the solvent is changed from methylene chloride–cyclohexane to ethanol.[12] To aid the interpretation of the spectra of **2a**, **b**, **3a**, **b** and **c**, CNDO/S calculations of transition energies and polarizations and of oscillator strengths have been performed for the simplified models **4**, **5** and **6** with geometries taken from ref. 6. In order to simplify the analysis of the symmetry of the transitions, the twist angle was taken to be 90°. The results of the calculations are found in Table 3.



4 X = O
5 X = S



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The spectrum of **2a** in methylene chloride–cyclohexane displays a medium-weak shoulder at 295 nm and two strong bands at 260 and 250 nm (Table 2). In ethanol, the first band disappears due to a strong blue-shift, while the second is shifted to 272 nm and the third to 229 nm. CNDO/S calculations for **4** predict three forbidden transitions in the range 482 to 355 nm, ascribed to $\pi_z \rightarrow \pi_y^*$, $n_- \rightarrow \pi_z^*$, and $n_+ \rightarrow \pi_z^*$ transitions respectively. n_- And n_+ are the antisymmetric and symmetric combinations of the lone pair orbitals of the carbonyl groups,[13] π_z indicates the π orbitals in the O–C–C–C–O system and π_y the corresponding orbitals in the CN_2 system. A weakly allowed transition of $n_- \rightarrow \pi_y^*$ type is predicted at 280 nm, and strong $\pi_z \rightarrow \pi_z^*$ transitions at 242 and 235 nm (Table 3). The observed three absorption bands may be assigned to the three latter transitions.

The spectrum of **2b** in methylene chloride–cyclohexane shows

Table 2 Experimental UV spectra of **2a**, **b** and **3a**

Compd.	Solvent (v/v)	λ_{max}/nm	ε/mol dm^{-3} cm^{-1}
2a	CH_2Cl_2–C_6H_{12} (1 : 9)	295(s)[a]	4 400
	CH_2Cl_2–C_6H_{12} (1:39)	260	21 800
		250(s)	21 600
	EtOH	272	21 000
		229	24 000
		202	31 500
2b	CH_2Cl_2–C_6H_{12} (1:9)	514	270
	CH_2Cl_2–C_6H_{12} (1:99)	422	57 700
		284	5 470
		229	27 100
	EtOH	490	31
		419	50 800
		350	660
		264	6 500
		226	26 000
3a	CH_2Cl_2–C_6H_{12} (1:9)	410(s)	6 400
	CH_2Cl_2–C_6H_{12} (1:99)	364	8 300
		230(s)	22 300
	EtOH	334	13 900
		280(s)	7 300
		220(s)	25 800

[a] Shoulder.

Table 3 Calculated spectra of models **4**, **5** and **6** with 90° twist. The coordinate system has the *x*-axis along the C-1–C-2 bond and the *z*-axis in the N-1–N-2 direction

Model	λ_{max}/nm	f[a]	Assignment	Polarization
4	280	0.006	$n_{-}\to\pi_y^*$	*x*
	242	0.196	$\pi_z\to\pi_z^*$	*y*
	235	0.145	$\pi_z\to\pi_z^*$	*y*
5	501	0.000	$n_{-}\to\pi_z^*$	—
	471	0.000	$\pi_z\to\pi_y^*$	—
	372	0.199	$\pi_z\to\pi_z^*$	*y*
	336	0.015	$n_{-}\to\pi_y^*$	*x*
	275	0.375	$\pi_z\to\pi_z^*$	*y*
6	565	0.000	$\pi_z\to\pi_y^*$	—
	419	0.013	$n\to\pi_y^*$	*x*
	396	0.000	$n\to\pi_z^*$	—
	293	0.294	$\pi_z\to\pi_z^*$	*y*
	227	0.057	$\pi_z\to\pi_z^*$	*xy*

[a] Oscillator strength.

a weak band in the visible region (514 nm) and strong bands at 422 and 229 nm. These absorption bands are reasonably assigned to the $n_{-}\to\pi_z^*$ and two $\pi_z\to\pi_z^*$ transitions predicted for **5** at 501, 372 and 275 nm respectively. The shift of the $n_{-}\to\pi_z^*$ band to 490 nm in ethanol is as expected.

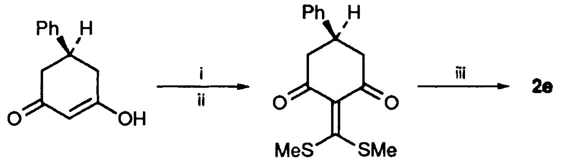
The medium strong shoulder observed at 410 nm in the spectrum of **3a** in methylene chloride–cyclohexane may be ascribed to the $n\to\pi_y^*$ transition predicted for **6** at 419 nm, and the stronger bands at 364 and 230 nm to $\pi_z\to\pi_z^*$ transitions predicted at 293 and 227 nm. No bands corresponding to forbidden $\pi_z\to\pi_y^*$ and $n\to\pi_z^*$ transitions predicted at 565 and 396 nm are observed. The shoulder at 410 nm and the 364 nm band appear unresolved at 334 nm in ethanol solution. In the spectra of **3b** and **c** in acetonitrile (Table 4) they appear as one broad band in the UV spectrum but as two well resolved bands of opposite signs in the CD spectrum.

The geometric differences between the molecules **3b** and **c** affect the positions of the absorption bands. The angle between the C–N bonds in the donor ring is *ca.* 108° in **3b**[5] and *ca.* 120° in **3c**.[6] The twist angle in the latter is *ca.* 70°[6] and probably somewhat smaller in **3b**. Experimentally, the CD bands of **3c** appear at longer wavelengths than the corresponding bands for **3b**, and calculations on modified structures **6** with C–N–C angles of 120° and 108° and twist angles of 70° and 65° respectively reproduce the observed wavelength differences with the correct orders of magnitude.

It follows from Table 4 that the signs of corresponding CD bands for the second eluted enantiomers of **3b** and **c** are in general opposite. It is reasonable to assume that they have opposite absolute configurations, and consequently the elution order with respect to the absolute configuration is opposite for the two compounds.

Experimental

Material.—The preparation of compounds **2a–d** and **3a–c** has been described earlier.[14] The preparation of **2e** follows Scheme 1.



Scheme 1 *Reagents:* i, NaH, CS_2; ii, MeI; iii, $Pr^iNH(CH_2)_3NHCH_2Ph$

2-(*Bismethylthio*)*methylene*-5-*phenylcyclohexane*-1,3-*dione* (**7**). 5-Phenylcyclohexane-1,3-dione (0.05 mol), prepared by reaction of diethyl malonate with benzalacetone in the presence of sodium ethoxide, essentially as described by Cooks *et al.*,[15] and carbon disulfide (0.075 mol) in dry dimethylformamide (DMF) (20 cm^3) was added dropwise to a stirred, ice-cooled suspension of sodium hydride (0.1 mol) in dry DMF (50 cm^3). After 45 min with cooling, 4 h at ambient temperature and 15 min at 50 °C the red solution was allowed to come to ambient temperature. Methyl iodide (0.12 mol) in DMF (10 cm^3) was added, and the solution was stirred overnight and then concentrated under reduced pressure. The residue was dissolved in CH_2Cl_2 and washed several times with water. Evaporation gave a pale yellow crystalline mass, 11.7 g (80% yield), long pale-yellow prisms, m.p. 134.5–135 °C, after recrystallization (toluene); δ_H(300 MHz, $CDCl_3$) 2.488 (s, 6 H), 2.72–2.95 (m, 4 H, AB of ABX: δ_A 2.788, δ_B 2.891, J_{AB} 17.0, J_{AX} 11.4, J_{BX} 4.5 Hz), 3.31–3.43 (m, 1 H, X of AA'BB'X, δ_X 3.370) and 7.20–7.36 (m, 5 H); δ_C(75 MHz, $CDCl_3$) 21.84 (CH_3S), 46.08 (CH_2), 124.33 [*C*(CO)$_2$], 126.47, 126.87, 128.70, 142.15 (C_6H_5), 190.92 [*C*(SCH_3)$_2$] and 192.16 (CO); *m*/*z* (70 eV) 292 (M^+, 23%), 277 ($M^+ - CH_3$, 67), 245 ($M^+ - CH_3S$, 18), 231 (20), 173 (30), 147 (26), 131 (80), 99 (100), 85 (32) and 45 (41). (Found: M^+; 292.0588. Calc. for $C_{15}H_{16}O_2S_2$ *M*, 292.0591); ν(KBr)/cm^{-1} 1660s (C=O) and 1610s (C=C).

1-*Benzyl*-3-*isopropyl*-2-(2,6-*dioxo*-4-*phenylcyclohexylidene*)-*hexahydropyrimidine* (**2e**). Compound **7** (0.01 mol) and *N*-benzyl-*N*'-isopropyl-1,3-diaminopropane[1] in dry DMF (50 cm^3) were refluxed until after 6.5 h no evolution of methanethiol could be detected by the lead acetate test. The solvent was removed under reduced pressure and the residue (3.4 g, 86% yield) was purified by recrystallization from toluene–light petroleum to give off-white crystals, m.p. 90–91 °C; *m*/*z* (70 eV) 402 (M^+, 15), 385 (21), 359 [$M^+ - (CH_3)_2CH$, 16], 311 (12), 257 (11), 146 (18), 98 (35), 91 (100), 70 (30) and 41 (50) (Found: M^+; 402.2314. Calc. for $C_{26}H_{30}N_2O_2$ *M*, 402.2307); λ_{max}(MeCN)/nm (ε/mol dm^{-3} cm^{-1}) 276 (20 100), 229 (18 700, shoulder), 219 (23 000, shoulder) and 200 (32 900, end absorption).

Table 4 UV and CD[a] spectra of **3b** and **c** in acetonitrile

Compound	λ_{extr}/nm (ε or $\Delta\varepsilon$)
3b (UV)	344 (8700), 286 (s,[b] 6200), 243 (15 700), 206 (s, 22 000)
3b (CD)	353 (−2.0), 324 (+0.53), 292 (−2.71), 261 (+1.68), 245 (+1.18), 219 (−3.17)
3c(UV)	355 (7700), 280 (5700), 226 (18 700), 205 (s, 20 700)
3c(CD)	368 (+0.64), 332 (−1.10), 293 (+3.01), 248 (−2.03), 221 (+5.03)

[a] Second eluted enantiomer. [b] Shoulder.

Table 5 Capacity and selectivity factors[20] for **3b** and **c** in the chromatographic enantiomer separation on a tris(phenylcarbamoyl)-cellulose column. Solvent hexane–propan-2-ol (9:1, v/v). 1,3,5-Tri-*tert*-butylbenzene was used as a non-retained reference (void volume marker).

Compd.	k'_1	k'_2	α
3b	1.36	1.96	1.44
3c	1.49	2.02	1.36

NMR analysis showed the product to be a mixture of two diastereoisomers (denoted A and B) in the ratio 1:1.8. Isomers A and B could be cleanly separated by HPLC on a preparative Chromasil column with a 1:1 (v/v) mixture of absolute ethanol and heptane as eluent. Isomer A was eluted first.

Isomer A. δ_H(300 MHz; $CDCl_3$) 1.138 (d, 6 H, *J* 6.8 Hz), 2.034 (quint, 2 H), 2.60–2.76 (m, 4 H, AB of ABX: δ_A 2.647, δ_B 2.711, J_{AB} 16.2, J_{AX} 5.6, J_{BX} 12.3 Hz), 3.239 (t, 2 H), 3.30–3.40 (m, t, 2 H, and m, 1 H, X of AA'BB'X), 4.261 (sept, 1 H, *J* 6.8 Hz), 4.703 (s, 2 H) and 7.1–7.4 (m, 10 H); δ_C(75 MHz, $CDCl_3$) 19.69 (CCH_2C), 20.12 (CH_3), 38.41 (CH_2N), 38.49 (CH_2N), 43.38 (CH_2CO), 44.57 ($CHPh$), 53.60 [$CH(CH_3)_2$], 57.40 (CH_2Ph), 103.0 [$C(CO)_2$], 126.27 (CH), 126.81 (2 CH), 128.09 (CH), 128.44 (2 CH), 128.75 (2 CH), 128.98 (2 CH), 134.92 (quarternary C), 144.13 (quarternary C), 164.00 (CN_2) and 189.30 (CO).

Isomer B. δ_H(300 MHz; $CDCl_3$) 1.258 (d, 6 H, *J* 6.8 Hz), 2.034 (quint, 2 H), 2.55–2.73 (m, 4 H, AB of ABX: δ_A 2.622, δ_B 2.672, J_{AB} 16.1, J_{AX} 4.8, J_{BX} 11.5 Hz), 3.235 (t, 2 H), 3.377 (t, 2 H), 3.33–3.45 (m, 1 H, X of AA'BB'X), 4.513 (s, 2 H), 4.582 (sept, 1 H, *J* 6.8 Hz) and 7.1–7.4 (m, 10 H). δ(75 MHz; $CDCl_3$) 19.73 (CCH_2C), 20.25 (CH_3), 38.50 (CH_2N), 38.76 (CH_2N), 43.59 (CH_2CO), 44.64 ($CHPh$), 53.56 [$CH(CH_3)_2$], 57.44 (CH_2Ph), 103.0 [$C(CO)_2$], 126.27 (CH), 126.75 (2 CH), 128.01 (CH), 128.44 (2 CH), 128.67 (2 CH), 128.91 (2 CH), 134.73 (quarternary C), 144.15 (quarternary C), 163.50 (CN_2) and 189.23 (CO).

Chromatographic Enantiomer Separation.—Attempts to resolve **3b** and **c** by chromatography on swollen, microcrystalline TAC[16,17] were unsuccessful, but with tris(phenylcarbamoyl)-cellulose adsorbed on silica[18,19] as the chiral stationary phase and with hexane–propan-2-ol (9:1, v/v) as the mobile phase, reasonable separation occurred (Table 5),[20] and after recycling once, pure enantiomers were obtained.

Thermal Racemization of Compounds **3b** *and* **3c**.—The racemization of these compounds was studied using the eluate from the TAC column containing the first eluted enantiomer of the respective compounds in hexane–propan-2-ol (9:1, v/v). The solution was filled into glass ampoules, which were sealed and kept at 90–91 °C in a silicon oil thermostatted vessel. Ampoules were taken out of the vessel at suitable time intervals, rapidly cooled and opened, and the solution was analysed by recording UV and CD spectra. As followed from the fall-off of the UV absorption with time, some thermal decomposition occurred, and correction for this was applied based on the UV absorption. The rate constants and free energy barriers to rotation are found in Table 1.

Thermal isomerization of **2e**. A sample of isomer A, 95.4% purity, was dissolved in toluene ($[A]_0 = 5 \times 10^{-3}$ mol dm^{-3}), and the solution was filled into glass ampoules, which were sealed and kept at 89.9 °C in a vessel as above. Analysis was performed with HPLC with the same equipment as was used for the separation of isomers A and B. Treatment of the rotation as a reversible first order reaction (Scheme 2) leads to eqn. (1).[21]

$$A \underset{k_{-1}}{\overset{k_1}{\rightleftharpoons}} B \qquad K = [B]/[A] = k_1/k_{-1}$$

Scheme 2

The equilibrium constant $K = k_1/k_{-1}$ at 89.9 °C was found to be 1.31. Rate constants and free energies of activation for the A→B isomerization are found in Table 2. When eqn. (1) is

$$(k_1 + k_{-1}) \times t = \ln([A]_0 - [A]_\infty) - \ln([A]_t - [A]_\infty) \quad (1)$$

applied to the racemization process, the relation $k_{rot} = 0.5k_{rac}$ is obtained.

Instruments.—NMR spectra were recorded with a Varian Model XL-300 NMR spectrometer, mass spectra with a JEOL Model SX-102 mass spectrometer, UV spectra with a Cary Model 2290 spectrometer (0.1 cm cell) and CD spectra with a JASCO Model J-500A spectropolarimeter. The enantiomer resolution was performed with the equipment described by Isaksson and Roschester[22] (except for the columns). To record the CD spectra, the fractions containing the pure enantiomers were evaporated, carefully dried, and dissolved in acetonitrile (spectroscopic grade). The concentrations were monitored by recording the UV spectra.

CNDO/S Calculations.—These were performed with a program specifically parameterized for sulfur compounds[23] with two-centre Coulomb integrals calculated by the Nishimoto–Mataga technique[24] and with configuration interaction between the 20 lowest singly excited states.

Acknowledgements

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References

1 J. Sandström and U. Sjöstrand, *Tetrahedron*, 1978, **34**, 371.
2 D. Adhikesvalu, N. U. Kamath and K. Venkatesan, *Proc. Indian Acad. Sci. (Chem. Sci.)*, 1983, **92**, 449.
3 J. Sandström, *Top. Stereochem.*, 1983, **14**, 83.
4 J. Sandström, in *The Chemistry of Enamines*, ed. Z. Rappoport, Wiley, Chichester, 1994, p. 405.
5 J. Sandström, K. Stenvall, N. U. Sen and K. Venkatesan, *J. Chem. Soc., Perkin Trans. 2*, 1985, 1939.
6 Preceding paper: Agha Z.-Q. Khan, F.-L. Liao, J. Sandström and S.-L. Wang, *J. Chem. Soc., Perkin Trans. 2*, 1994, 1569.
7 J. Sandström, U. Sjöstrand and I. Wennerbeck, *J. Am. Chem. Soc.*, 1977, **99**, 4526.
8 U. Berg, R. Isaksson, J. Sandström, U. Sjöstrand, A. Eiglsperger and A. Mannschreck, *Tetrahedron Lett.*, 1982, **23**, 4237.
9 Agha Z.-Q. Khan, R. Isaksson and J. Sandström, *J. Chem. Soc., Perkin Trans. 2*, 1987, 491.
10 Agha Z.-Q. Khan and J. Sandström, *Acta Chem. Scand.*, 1992, **46**, 897.
11 Agha Z.-Q. Khan, J. Sandström and S.-L. Wang, *J. Chem. Soc., Perkin Trans. 2*, 1991, 913.
12 J. W. Sidman, *Chem. Rev.*, 1958, **58**, 689.

13 L. Fälth, U. Håkansson and J. Sandström, *J. Mol. Struc. (Theochem)*, 1989, **186**, 239.

14 Agha Z.-Q. Khan and J. Sandström, *J. Org. Chem.*, 1991, **56**, 1902.

15 R. G. Cooks, D. H. Williams, K. M. Johnson and J. D. Stride, *J. Chem. Soc. C*, 1968, 2199.

16 A. Mannschreck, H. Koller and R. Wernicke, *Merck Kontakte*, 1985, **1**, 40.

17 R. Isaksson, P. Erlandsson, L. Hansson, A. Holmberg and S. Berner, *J. Chromatogr.*, 1990, **498**, 257.

18 A. Ishida, T. Shibata, I. Okamoto, Y. Yuki, H. Namikoshi and Y. Toga, *Chromatographia*, 1984, **19**, 280.

19 P. Erlandsson, R. Isaksson, P. Lorentzon and P. Lindberg, *J. Chromatogr., Biomed. Appl.*, 1990, **532**, 305.

20 S. Allenmark, *Chromatographic Enantioseparation. Methods and Applications*, 2nd ed., Ellis Horwood, London, 1991, p. 51.

21 A. A. Frost and R. G. Pearson, *Kinetics and Mechanism*, Wiley, New York 1960, p. 172.

22 R. Isaksson and J. Roschester, *J. Org. Chem.*, 1985, **50**, 2519.

23 C. Guimon, D. Gonbeau and G. Pfister-Guillouzo, *Tetrahedron*, 1973, **29**, 3399.

24 K. Nishimoto and N. Mataga, *Z. Phys. Chem.*, 1957, **12**, 335.

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