Conformation and stereodynamics of alkyl 9-anthryl sulfoxides

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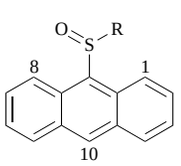
Several alkyl 9-anthryl sulfoxides exhibit broadening of the aromatic *peri*-proton signal in ^{1}H NMR spectra recorded at ambient temperature due to hindered rotation about the 9-anthryl–sulfur bond; the rotational barriers lie in the range 10.9–18.9 kcal mol^{-1}. The preferred conformation and torsional barriers in these sulfoxides and in mesityl methyl sulfoxide have also been investigated by molecular mechanics calculations.

There have been few reports of high barriers to rotation about carbon–sulfur single bonds.[1] The length of the C–S bond, as compared with say a C–C bond, reduces steric interactions between vicinal substituents and a low torsional barrier would normally be expected. However, examination of the ^{1}H NMR spectrum of a sample of 9-anthryl methyl sulfoxide (**1**) prepared in this laboratory showed selective broadening of a doublet aromatic signal at δ 9.10 in deuteriochloroform, integrating for two protons. A variable temperature NMR study was undertaken on this and related sulfoxides to establish the reason for this selective line broadening.

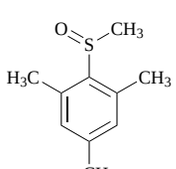
Discussion

NMR spectra

On lowering the temperature of a solution of **1** in CD_2Cl_2, the signal at δ 9.1 broadened further and below −20 °C it collapsed into the baseline. At around −50 °C two new broad signals, each 1 H, emerged and at −70 °C they had sharpened into two doublet signals (J 8.8 Hz) at δ 8.59 and 9.60. These doublet signals are assigned to the *peri* protons H-1 and H-8 on the 9-anthryl ring which are clearly non-equivalent in chemical shift at low temperatures.



1 R = Me
2 R = Bu^n
3 R = Bu^i
4 R = Bn
5 R = Pr^i
6 R = Bu^t



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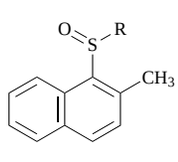

8a R = Me
8b R = Et
8c R = Pr^i
8d R = Bu^t

Slow rotation about the 9-anthryl–sulfoxide bond is the only viable explanation of the H-1/H-8 non-equivalence. Some dynamic exchange effects were also observable on the other aromatic signals at low temperatures, but signal overlap in the δ 7.5–8.3 region restricted detailed analysis. As expected, the H-10 singlet signal at δ 8.61 did not exhibit any exchange broadening effects as it lies on the rotational axis and hence is not affected by slow rotation about the ring–sulfur bond. Sulfoxides **2**–**6** exhibit similar dynamic NMR effects but at increasingly higher temperatures as the steric bulk of the *S*-R group increases (Table 1). Indeed the most hindered *tert*-butyl compound **6** shows nonequivalent H-1 and H-8 doublet signals at ambient temperature (δ 8.62 and 9.78 in $CDCl_3$) and coalescence was not fully achieved at 100 °C in deuteriated 1,1,2,2-tetrachloroethane, at which temperature the compound decomposed rapidly.

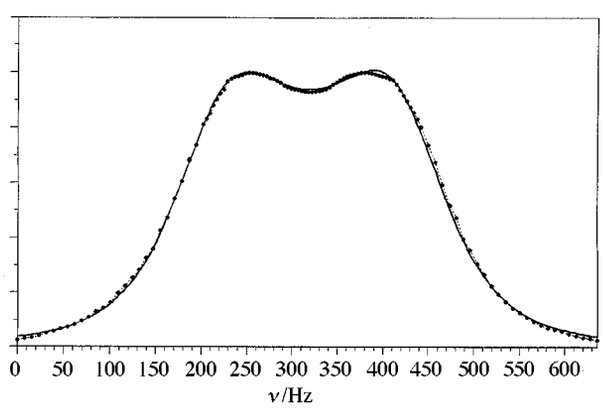

Fig. 1 Experimental (●) and best fit calculated (—) ^{1}H NMR lineshapes for the *peri*-proton signal of sulfoxide **1** at −34.4 °C in CD_2Cl_2 (k = 522 s^{-1})

Lineshape analysis of the exchange broadened *peri* proton signal in the region of coalescence for compounds **1**–**6** gave the rate constant (k). The free energy barriers ($\Delta G^{\ddagger}$) for the rotational process, calculated from the Eyring equation, are given in Table 1. The system was analysed as a four-site coalescence of two doublets (J 8.8 Hz) to a single doublet. In some cases other aromatic signals partly overlapped the coalescing H-1/H-8 bandshape but sufficient signal was visible to enable digitisation and computer analysis. A representative calculated and experimental lineshape for compound **1** is depicted in Fig. 1. Although the barriers were necessarily determined at different temperatures, a comparison is meaningful since the entropy of activation is normally small for an intramolecular rotational process of the type observed here.

The rotational barrier increases markedly with the bulk of the *S*-alkyl group indicative of a sterically dominated process involving passage of the alkyl group past either *peri*-hydrogen. The only unexpected result in the general trend is that the *S*-benzyl compound (**4**) has a higher barrier than the *S*-isobutyl analogue (**3**), close to that in the *S*-isopropyl compound (**5**). Possibly there is some unfavourable interaction in the rotational transition state involving the benzylic ring.

Restricted rotation about aryl–S(O) bonds has previously been reported by Buchanan[2] in the mesityl sulfoxide **7** ($\Delta G^{\ddagger}$ 9.2 kcal mol^{-1}) and more recently by Casarini *et al.*[3] in the 1-naphthyl sulfoxides **8a**–**d** ($\Delta G^{\ddagger}$ 10.6, 12.2, 13.4 and 18.4 kcal mol respectively for the major ⟶ minor rotamer). The

Table 1 Dynamic ^{1}H NMR data for rotation around the 9-anthryl–sulfur bond in sulfoxides **1**–**7**

Comp.	R	$\delta\nu$/Hz[a]	T/°C[b]	k/s^{-1}	$\Delta G^{\ddagger}$/kcal mol^{-1}[c]	V_{calc}/kcal mol^{-1}[d]
1	Me	279[e]	−34.4	522	10.9	11.6
2	Bu^n	260[e]	4.8	522	12.8	13.1
3	Bu^i	416[f]	18.5	811	13.2	13.1
4	$PhCH_2$	386[e]	14.7	256	13.7	13.0
5	Pr^i	244[e]	28.3	475	14.0	14.6
6	Bu^t	311[g]	98.0	61	18.9	20.8
7	Me	96.3[h]	−94.0[h]	214	8.4[h]	8.6

[a] Signal separation of the non-equivalent *peri*-protons in the absence of exchange effects. [b] Probe temperature at which the exchange rate (k) was determined; compounds **1**, **2**, **3**, **5** and **7** were close to the coalescence point and **4** and **6** were below coalescence. [c] Free energy barrier determined by NMR (1 kcal = 4.184 kJ). [d] Rotational barrier calculated by MMX (1 kcal = 4.184 kJ). [e] Determined in CD_2Cl_2 solution at 270 MHz. [f] Determined in CD_2Cl_2 solution at 400 MHz. [g] Determined in deuterio-1,1,2,2-tetrachloroethane solution at 270 MHz. [h] Determined from the coalescing *ortho*-methyl signals in CD_2Cl_2 solution at 300 MHz.

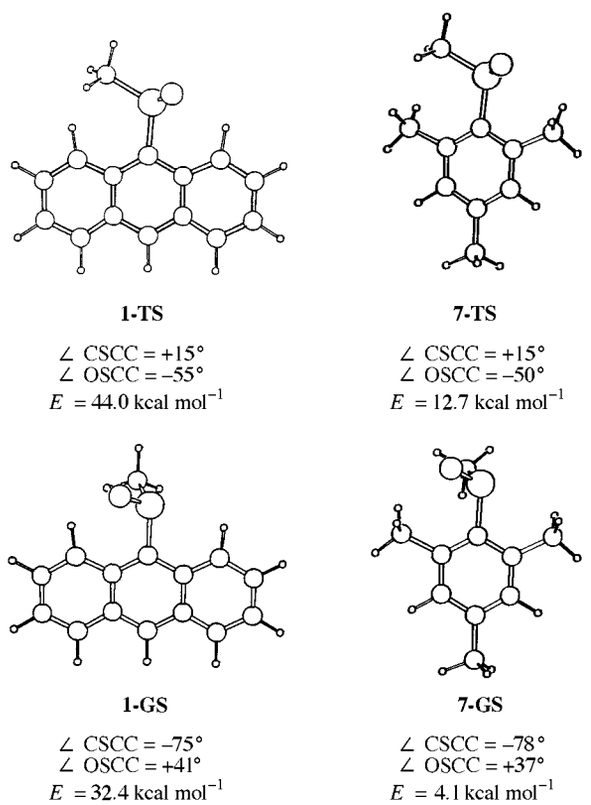

Fig. 2 Calculated ground-state (GS) and torsional transition-state (TS) geometries for sulfoxides **1** and **7**; the CSCC and OSCC torsion angles are cited with respect to the quaternary *ortho*-carbon nearest to the CH_3–S or O–S group respectively

rotational barrier in **7** has been remeasured in the present investigation at 8.4 kcal mol^{-1} in deuteriodichloromethane solution (Table 1) as the previously reported value of 9.2 kcal mol^{-1} was determined in carbon disulfide–deuteriochloroform. In view of the appreciable difference between the S–Ar rotational barrier in **7** reported in this paper and the $\Delta G^{\ddagger}$ value reported previously in ref. 2, we have also remeasured the barrier in CS_2–$CDCl_3$ on a modern 300 MHz spectrometer giving $\Delta G^{\ddagger} = 8.5$ kcal mol^{-1} at −96 °C ($\Delta\nu = 92.4$ Hz, $k = 120$ s^{-1}). This value is significantly lower than that reported in ref. 2 ($\Delta G^{\ddagger}$ 9.2 kcal mol^{-1}). The fact that the barrier in the mesityl compound **7** is 2.5 kcal mol^{-1} lower than that in the 9-anthryl compound **1** would tend to suggest that it is significantly easier for a *S*-methyl to pass an *ortho*-methyl group than a *peri*-hydrogen. On this basis one might expect aryl–S(O) rotation in compound **8a** to occur more readily by rotation of the *S*-methyl group past the 2-methyl group. This suggestion is in agreement with previous indications[3] from molecular mechanics calculations on **8a**, though the measured rotational barriers in **8a** ($\Delta G^{\ddagger}$ 9.8/10.6 kcal mol^{-1})[3] are higher than the barrier in **7** ($\Delta G^{\ddagger}$ 8.4 kcal mol^{-1}).

Molecular mechanics calculations

MMX calculations on the representative *S*-methyl compound (**1**) indicate a ground-state conformation with a torsion angle of 75° between the S–Me bond and the plane of the 9-anthryl ring (Fig. 2). The *S*-methyl group is rotated 15° out of orthogonality with the anthryl ring in a direction that moves the sulfoxide group further out of the ring plane. The calculated O–S–C–C torsion angle is 41°. Presumably this arrangement reduces steric interactions between the sulfoxide group and the neighbouring *peri*-hydrogen.

The other 9-anthryl sulfoxides **2**–**6** have similar calculated ground-state geometries with R–S–C–C torsion angles in the range 70–80°. The sulfoxide group in compounds **1**–**6** is sufficiently close to one *peri*-hydrogen for its anisotropy to deshield this signal to the observed shift of δ 9.4–9.8 in the slow exchange limit. The mesityl sulfoxide **7** is calculated to have similar preferred geometry with Me–S–C–C and O–S–C–C torsion angles of −78 and 37° respectively (Fig. 2).

The molecular mechanics calculations indicate that the torsional transition-state in **1** and **7** occurs when the *S*-methyl group is 15° out of the anthryl ring plane and the sulfoxide bond is −55 and −50° respectively out of the plane on the same face as the *S*-methyl group (Fig. 2). The torsional transition state lacks symmetry hence it is not unexpected that the *S*-methyl group does not lie precisely in the ring plane at the energy maximum. The small 15° torsional distortion places the sulfoxide group slightly closer to the *peri*-hydrogen in **1** (or *ortho*-methyl group in **7**) than would be the case were the *S*-methyl group precisely in the ring plane. However the sulfoxide group is *ca.* 15° further out of the ring plane in the torsional transition-state than in the ground-state indicating that, as expected, the barrier is largely dominated by steric interactions involving the *S*-alkyl group and the neighbouring *peri*-hydrogen or *ortho*-methyl group.

The calculated potential energy barriers for rotation in compounds **1**–**7** are in satisfactory agreement with the free energy barriers determined by NMR (Table 1), bearing in mind that the measured $\Delta G^{\ddagger}$ values include entropy effects. Only in the case of the very hindered *tert*-butyl compound **6** does the difference between the calculated and experimental barrier exceed 0.7 kcal mol^{-1}. This supports the view that the rotational barrier is predominantly energetic and that the entropy effects play a minor role. The calculations confirm that it is easier by *ca.* 3.0 kcal mol^{-1} for a *S*-methyl group to pass an *ortho*-methyl group in compound **7** than a *peri*-hydrogen in compound **1**. Previous MMX calculations on the 1-naphthyl sulfoxide **8a** indicated that the barrier for *S*-methyl passing an *ortho*-methyl group is 1.5–2.0 kcal mol^{-1} lower than for passing a *peri*-hydrogen.[3]

Experimental

9-(Chlorodithio)anthracene, mp 115–117 °C (lit.,[4] 117–118 °C) was prepared by treating anthracene with two equivalents of sulfur monochloride.[4] Reduction of 9-(chlorodithio)anthracene with lithium aluminium hydride or sodium bis(2-methoxyethoxy)aluminium hydride in diethyl ether–toluene afforded anthracene-9-thiol, mp 88–90 °C (lit.,[5] mp 87–91 °C).[5] 9-Anthryl methyl sulfide, mp 66–67 °C (lit.,[5] mp 65–66 °C) and 9-anthryl benzyl sulfide, mp 98–99 °C (lit.,[5] mp 99–100 °C) were obtained by alkylation of anthracene-9-thiol in 20% aqueous sodium hydroxide (containing a trace amount of sodium dithionite) with dimethyl sulfate and benzyl chloride respectively according to the procedure of Conway and Tarbell.[5] 9-Anthryl butyl sulfide, bp 114–116 °C/0.1 mmHg (lit.,[6] bp 125–128 °C/0.25 mmHg), 9-anthryl isobutyl sulfide, bp 100–103 °C/0.1 mmHg (lit.,[6] bp 112–115 °C/0.25 mmHg) and 9-anthryl isopropyl sulfide, mp 62–64 °C (lit.,[7] mp 64–66 °C) were prepared by alkylating sodium anthracene-9-thiolate (prepared from anthracene-9-thiol and sodium hydride in THF) with 1-bromobutane, 1-bromo-2-methylpropane and 2-bromopropane respectively.[7] Mesityl methyl sulfoxide (**7**) was prepared according to the general procedure described by Buchanan[2] except that methyl iodide in KOH was used as the methylating agent instead of dimethyl sulfate in NaOH.

9-Anthryl *tert*-butyl sulfide

According to the general procedure of Migita *et al.*,[8] sodium 2-methylpropane-2-thiolate (1.12 g, 10.0 mmol) and palladium tetrakis(triphenylphosphine) (0.12 g, 0.10 mmol) were added to 9-bromoanthracene (2.57 g, 10.0 mmol) in dry butan-1-ol (25 cm^3) under nitrogen, and the solution was heated under reflux for 6 h. Removal of the solvent under reduced pressure afforded an orange–brown solid (2.52 g, 95%) which was purified by flash-column chromatography on silica gel. Elution with light petroleum (bp 80–100 °C) afforded the sulfide as a yellow solid (1.41 g, 53%), mp 142–144 °C (Found: C, 81.2; H, 6.8. $C_{18}H_{18}S$ requires C, 81.2; H, 6.8%); $\delta_H(CDCl_3)$ 1.22 (9H, s, 3 × Me), 7.2–9.2 (9H, m, aromatic).

Preparation of sulfoxides

Sulfoxides were obtained by oxidising the respective sulfides with one equivalent of 70% *m*-chloroperoxybenzoic acid in dichloromethane at −15 °C. The solution was washed with 5% aqueous sodium sulfite, 5% aqueous sodium hydrogen carbonate, water, and dried. Removal of the solvent afforded the crude sulfoxide (70–90%) as an orange oil. These alkyl 9-anthryl sulfoxides could not be obtained sufficiently pure for accurate microanalysis due to their slow decomposition on silica or alumina and their limited thermal stability on heating. However the precursor sulfides were well characterised (see above) and ^{1}H NMR spectra † and MS data of the sulfoxides were in accord with their structure.

9-Anthryl methyl sulfoxide 1. (Found: M^+, 240.062. $C_{15}H_{12}OS$ requires *M*, 240.061); $\delta_H(CDCl_3)$ 3.15 (3H, s, Me), 7.5–8.6 (7H, m, aromatic) and 9.05 (2H, br d, aryl H-1 and H-8).

9-Anthryl butyl sulfoxide 2. (Found: M^+, 282.105. $C_{18}H_{18}OS$ requires *M*, 282.108); $\delta_H(CDCl_3)$ 0.79 (3H, t, Me), 1.40 (4H, m, 2 × CH_2), 2.82 (2H, m, SCH_2) and 7.4–9.6 (9H, m, aromatic).

† *J* Values are given in Hz.

9-Anthryl isobutyl sulfoxide 3. (Found: M^+, 282.107. $C_{18}H_{18}OS$ requires *M*, 282.108); $\delta_H(CDCl_3)$ 1.14 (3H, d, Me), 1.17 (3H, d, Me), 2.30 (1H, m, C*H*Me_2), 2.81 (1H, dd, SCH), 3.74 (1H, dd, SCH) and 7.5–9.6 (9H, m, aromatic).

9-Anthryl benzyl sulfoxide 4. (Found: M^+, 316.091. $C_{21}H_{16}OS$ requires *M*, 316.092); $\delta_H(CDCl_3)$ 4.52 (1H, d, ^2J 12.2, SCH), 4.73 (1H, d, ^2J 12.2, SCH) and 6.8–9.6 (14H, m, aromatic).

9-Anthryl isopropyl sulfoxide 5. (Found: M^+, 268.091. $C_{17}H_{16}OS$ requires *M*, 268.092); $\delta_H(CDCl_3)$ 0.84 (3H, d, ^3J 7.0, Me), 1.65 (3H, d, ^3J 7.0, Me), 4.00 (1H, septet, ^3J 6.8, SCH), 7.5–9.6 (7H, m, aromatic) and 9.45 (2H, br d, aryl H-1 and H-8).

9-Anthryl *tert*-butyl sulfoxide 6. (Found: M^+, 282.108. $C_{18}H_{18}OS$ requires *M*, 282.108); $\delta_H(CDCl_3)$ 1.34 (9H, s, 3 × Me), 7.2–8.6 (7H, m, aromatic), 8.62 (1H, d, aryl H-1) and 9.78 (1H, d, aryl H-8).

Dynamic NMR studies

Variable temperature ^{1}H NMR spectra were recorded at 270 MHz on a JEOL GSX-270 spectrometer or at 400 MHz on a Bruker AMX-400 spectrometer. Probe temperatures were calibrated using a digital thermometer equipped with a fine-gauge copper–constantan thermocouple lead inserted in a non-spinning sample tube containing 0.7 cm^3 of solvent. Exchange broadened spectra were analysed using a PC version of the iterative multisite exchange program INMR.[9] The doublet splitting of the exchanging *peri*-protons was included in the analysis as a four-site exchange system.

Molecular mechanics calculations

These calculations were performed using the MMX force field as implemented in the program PC Model by Serena Software, Bloomington, Indiana. As no particular parameters were available for sulfoxides the default values were employed. The torsional barriers were determined by driving the Ar–SO torsion angle in small steps in the vicinity of the energy minimum and maximum, allowing the other angles and bond lengths to relax to their minima at each value of the Ar–SO torsion angle.

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