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The Crystal and Molecular Structure of *endo*-3-Benzylsulfinylbicyclo[2.2.1]heptane-*endo*-2-carboxylic Acid

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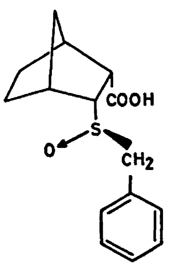
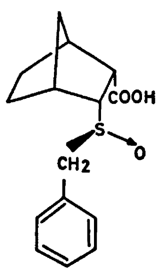
The title compound ($C_{15}H_{18}O_3S$) crystallizes in space group $C2/c$, with 8 molecules in a unit cell of dimensions $a=24.768$, $b=10.116$, $c=12.611$ Å and $\beta=118.05°$. The structure determination was accomplished *via* the heavy-atom method and led to a refined set of parameters with $R=0.042$ for 1461 observed reflexions. The compound investigated is the more reactive of two configurational isomers. The sulfinyl and carboxyl groups of different molecules are hydrogen-bonded. An intramolecular non-bonded close contact of 2.80 Å between the sulfur atom and the carbonyl oxygen provides an intramolecular proximity between these two groups, with an $O-S\cdots O$ angle of 173°. The study gives structural evidence for the anchimeric effects used to explain the solution kinetics of this and similar compounds.

The crystal structure of *endo*-3-benzylsulfinylbicyclo[2.2.1]heptane-*endo*-2-carboxylic acid (Ia) was determined in connection with kinetics studies of certain sulfinyl derivatives being investigated by Allenmark.[1,2]

In the hydriodic acid reduction of a sulfoxide the rate-accelerating effect of a neighbouring carboxyl group has been demonstrated. The reaction proceeds with formation of a cyclic sulfonium intermediate as the rate determining step. There is also strong evidence for an inversion mechanism in forming the cyclic intermediate.



Ia



Ib

For the particular case involving (I), one of the diastereoisomers showed a rate constant more than 3000 times greater than the other.[2b] The diastereoisomers Ia and b differ only in their configuration about sulfur, but for each of them there exists a pair of mirror image isomers. This X-ray analysis concerns the racemate of the more reactive diastereoisomer.

EXPERIMENTAL

Good single crystals were found in samples kindly supplied by Dr. Stig Allenmark of Uppsala University. The compound had been recrystallized from a water-ethanol solution. The specimen chosen for investigation was a colourless rectangular prism of approximate dimensions $0.3\times0.25\times0.1$ mm. The systematic absences observed were for the hkl reflexions with $h+k$ odd, and for the $h0l$ reflexions with l odd. As the compound is a racemate and had a measured density in agreement with eight molecules in the unit cell of the two possible spacegroups, Cc or $C2/c$, the latter was the more logical choice. Later refinement of the structure verified that this choice was correct. The lattice constants given below were obtained from least squares refinement of the diffractometer setting angles of 12 reflexions. The intensity data were taken on Picker FACS I diffractometer supplied with a graphite monochromator using Cu$K\alpha_1$ radiation. The $\theta-2\theta$ scanning mode at a rate of 1°/min and a scan width of 2° adjusted for dispersion were used. Two ten-second background counts were taken at each end of the scan. Attenuation was used where reflexions exceeded 10.000 cps.

Measuring all reflexions out to a 2 θ of 110° provided 1461 independent reflexions greater than 2 σ above background. Three reflexions were monitored following every 50 measurements. The standard showing the greatest change had a root-mean-square deviation of 2.5 %.

Changes in the sum of the standard intensities were interpolated in a linear fashion and applied as scaling factors to the rest of the data. The intensities were also corrected for Lorentz and polarization effects but not for absorption.

CRYSTAL DATA

Molecular formula	$C_{15}H_{18}O_3S$
Molecular weight	278.373 g/mol
Space group	$C2/c$ (No. 15)
Cell constants	$a = 24.768(5)$, $b = 10.116(2)$, $c = 12.611(2)$ Å, $\beta = 118.05(5)°$
Unit cell volume	2788.46 Å^3
Calculated density ($Z = 8$)	1.326 g cm^{-3}
Measured density	1.31 g cm^{-3}
Linear absorption coefficient (Cu$K\alpha$)	20.1 cm^{-1}

STRUCTURE DETERMINATION

The sulfur coordinates were readily obtained from a three-dimensional Patterson synthesis. A subsequent three-dimensional Fourier synthesis based on the observed data and the phases obtained from the sulfur position, yielded the coordinates of seven additional atoms in the vicinity of the sulfur atom. The remaining non-hydrogen atoms were obtained at heights of 2 – 5 e$^-$/Å^3, from an electron density map based on the positions of the eight atoms previously found. Three cycles of least squares refinement, using anisotropic thermal parameters for the sulfur atom, gave $R = 0.12$. At this point a difference Fourier was calculated from which all but one of the hydrogens could be identified near their calculated positions and at heights from 0.5 to 1 e$^-$/Å^3. Using these hydrogen positions only in the structure factor calculations, anisotropic refinement of all non-hydrogen atoms led to an $R = 0.052$. With these positions fixed, subsequent isotropic refinement of only the hydrogen positions resulted in an $R = 0.044$. On the resulting difference Fourier a single peak appeared at a height of about 0.4 e$^-$/Å^3, in the region between the hydroxyl and sulfinyl oxygens. Assignment of this peak as a hydrogen atom and repeating the difference synthesis gave an electron density map with no point greater than 0.2 e$^-$/Å^3.

Since several of the largest structure factors with a sin θ/λ less than 0.2 were systematically as much as 10 % lower than the corresponding calculated values, it was assumed that these 28 reflexions suffered from extinction. They were removed from the last three cycles of refinement, which led to a final $R = 0.042$. Since the largest shift in either a coordinate or temperature factor was less than three-tenths of its corresponding standard deviation, the structure determination was now considered complete.

The atomic scattering factors for all atoms except hydrogen were taken from the International Tables for X-ray Crystallography.[3] The scattering factor for sulfur was corrected for the effect of anomalous dispersion (real part). The hydrogen scattering factor used was that given by Stewart, Davidson and Simpson.[4] The weighting scheme used in the refinement was that of Mills and Rollett.[5]

RESULTS AND DISCUSSION

A list of the final structure factors can be obtained from this laboratory. Coordinates

Table 1. Fractional coordinates with standard deviations in parentheses.

	x	y	z
S(1)	0.2370(1)	0.1310(2)	0.1489(1)
O(1)	0.2407(2)	0.2209(4)	0.2484(4)
O(2)	0.2402(3)	−0.0111(6)	−0.0383(5)
O(3)	0.3017(2)	−0.1765(5)	−0.0267(4)
C(1)	0.3638(3)	0.1293(7)	0.2789(6)
C(2)	0.3076(3)	0.0362(7)	0.2237(5)
C(3)	0.3250(3)	−0.0657(7)	0.1529(6)
C(4)	0.3902(3)	−0.0204(8)	0.1804(7)
C(5)	0.3855(3)	0.1089(9)	0.1133(8)
C(6)	0.3664(4)	0.2109(8)	0.1796(7)
C(7)	0.4151(3)	0.0289(9)	0.3085(7)
C(8)	0.2840(3)	−0.0792(7)	0.0209(6)
C(9)	0.1837(3)	0.0011(7)	0.1400(7)
C(10)	0.1231(3)	0.0614(7)	0.1081(7)
C(11)	0.1089(4)	0.0980(9)	0.1978(8)
C(12)	0.0543(5)	0.1584(11)	0.1705(12)
C(13)	0.0135(5)	0.1828(10)	0.0554(13)
C(14)	0.0256(4)	0.1484(11)	−0.0357(10)
C(15)	0.0812(4)	0.0862(9)	−0.0101(8)

Table 2. Anisotropic thermal parameters ($\times 10^4$) in the form $\exp[-2\pi^2(h^2a^{*2}U_{11}+k^2b^{*2}U_{22}+l^2c^{*2}U_{33}+2klb^*c^*U_{23}+2hla^*c^*U_{31}+2hka^*b^*U_{12})]$. Standard deviations are given in parentheses.

	U_{11}	U_{22}	U_{33}	U_{23}	U_{31}	U_{12}
S(1)	418(9)	347(9)	452(9)	25(7)	22(7)	2(7)
O(1)	594(32)	368(27)	512(27)	−17(22)	307(25)	47(23)
O(2)	695(36)	695(37)	519(31)	−75(28)	197(28)	158(31)
O(3)	709(35)	475(30)	555(30)	−23(25)	373(28)	72(26)
C(1)	453(40)	514(42)	453(41)	−45(35)	138(34)	−32(35)
C(2)	423(38)	407(39)	406(36)	43(31)	224(31)	−2(31)
C(3)	484(40)	370(38)	482(39)	62(31)	277(33)	11(31)
C(4)	464(43)	573(49)	676(48)	−20(41)	311(38)	40(37)
C(5)	659(53)	721(58)	738(55)	0(46)	440(46)	−168(45)
C(6)	550(49)	515(48)	707(50)	−1(40)	295(42)	−127(39)
C(7)	432(43)	685(55)	648(49)	8(42)	184(38)	8(40)
C(8)	526(41)	414(38)	521(41)	31(34)	301(35)	−40(34)
C(9)	481(42)	389(40)	729(50)	31(36)	313(39)	−39(33)
C(10)	436(42)	363(39)	682(48)	52(35)	260(38)	−70(32)
C(11)	484(47)	660(56)	919(63)	−106(48)	361(46)	−86(41)
C(12)	688(61)	798(70)	1667(109)	−277(72)	732(71)	−136(54)
C(13)	564(62)	628(64)	2148(144)	217(79)	577(76)	−10(50)
C(14)	611(57)	820(70)	1231(87)	568(65)	55(57)	−130(53)
C(15)	561(50)	727(59)	729(57)	246(48)	165(44)	−133(45)

Table 3. Fractional atomic coordinates and isotropic temperature factors for the hydrogen atoms. Estimated standard deviations in parentheses.

	x	*y*	*z*	*B*(Å^2)
H(1,1)[a]	0.369(3)	0.175(6)	0.343(5)	4.1(1.3)
H(2,1)	0.303(2)	−0.008(6)	0.286(5)	2.9(1.2)
H(3,1)	0.327(2)	−0.150(5)	0.189(5)	2.6(1.2)
H(4,1)	0.411(3)	−0.087(6)	0.168(5)	5.6(1.5)
H(5,1)	0.358(3)	0.104(6)	0.034(5)	4.8(1.5)
H(5,2)	0.426(3)	0.128(7)	0.120(6)	7.4(1.9)
H(6,1)	0.328(3)	0.255(6)	0.132(5)	6.2(1.5)
H(6,2)	0.396(3)	0.281(8)	0.215(7)	6.9(2.0)
H(7,1)	0.417(3)	−0.035(7)	0.365(6)	5.1(1.6)
H(7,2)	0.454(3)	0.066(7)	0.336(6)	5.8(1.7)
H(9,1)	0.199(3)	−0.034(6)	0.212(5)	4.7(1.5)
H(9,2)	0.183(3)	−0.162(6)	0.080(6)	4.8(1.5)
H(11,1)	0.140(3)	0.079(7)	0.276(6)	5.4(1.6)
H(12,1)	0.046(4)	0.177(9)	0.240(8)	8.4(2.3)
H(13,1)	−0.028(5)	0.221(10)	0.035(9)	11.5(2.9)
H(14,1)	0.000(4)	0.160(9)	−0.115(8)	9.1(2.5)
H(15,1)	0.092(4)	0.057(9)	−0.071(8)	9.4(2.4)
H(16)[b]	0.276(5)	−0.192(11)	−0.107(9)	11.5(3.1)

[a] The first number refers to the bonded atom. [b] Carboxyl hydrogen.

and anisotropic temperature factors for the non-hydrogen atoms are given in Tables 1 and 2, respectively. Hydrogen atom parameters are given in Table 3.

The atomic numbering and distances and angles for non-hydrogen atoms are shown in Fig. 1. The C−H distances range from 0.87 to 1.02 Å.

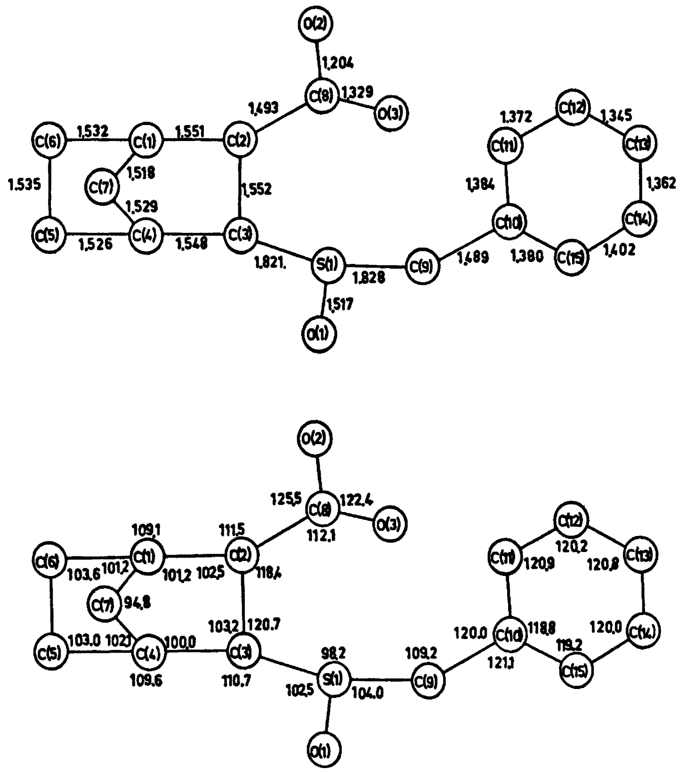


Fig. 1. Bond distances and angles. The average standard deviations are for the bonds S – C 0.005, S – O 0.003, C – C 0.007 and C – O 0.006 Å and for the angles C – S – C 0.2, C – S – O 0.2, C – C – C 0.4 and C – C – O 0.3°.

Table 4. Comparison of parameters about the sulfur atom.

Compound	C – S (Å)	S – O (Å)	C – S – O (°)	C – S – C (°)	O···S – O (°)	S···O (Å)	Ref.
o-Carboxyphenyl-methyl sulfoxide	1.788(5) 1.800(3)	1.517(2)	103.1(0.1) 104.6(0.2)	97.8(0.2)	176	2.78	8
(–)-*o*-Carboxyphenyl-methyl sulfoxide	1.782(6) 1.800(5)	1.517(3)	103.7(0.2) 104.3(0.2)	98.8(0.2)	173	2.73	9
endo-3-Benzylsulfinyl-bicyclo[2.2.1]heptane-*endo*-2-carboxylic acid	1.821(6) 1.828(8)	1.517(6)	102.5(0.3) 104.0(0.4)	98.2(0.3)	173	2.80	This study

Except for the three slightly longer bonds involving the substituted ring carbon atoms C(2) and C(3), the distances and angles in the norbornyl portion of the molecule are within 1.5 σ of the parameters for norbornane found from a microwave study.[6] The distances C(2) – C(8) and C(9) – C(10) exhibit the expected shortening for a C – C single bond adjacent to a multiple bond. The parameters about the sulfur are in good agreement with those found for similar compounds, and the relevant values are listed for comparison in Table 4.

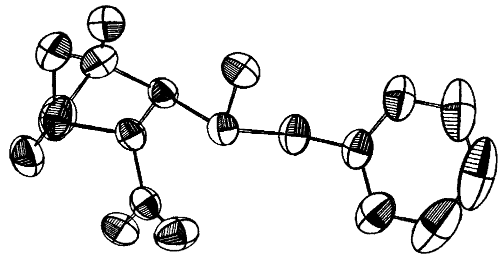


Fig. 2. Thermal ellipsoids at 50 % probability level.

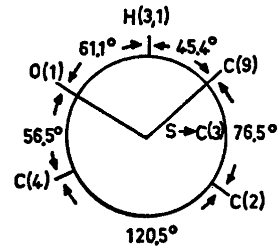


Fig. 3. Newman projection along the S(1)–C(3) bond.

The bond distances in the phenyl ring have an average value of 1.375 ± 0.013 Å (av. dev.), significantly shorter than the normal value of 1.394 Å. The shorter distances in the phenyl ring, particularly the two distances C(12)–C(13) and C(13)–C(14) are explained as an experimental artifact of the pronounced thermal motion in that region of the molecule (Fig. 2). The phenyl ring is planar to within ± 0.003 Å, and the internal angles are all within 1σ of 120°.

A Newman projection of one of the mirror image pairs of the structure viewed down the S(1)–C(3) bond is shown in Fig. 3 and establishes the configuration of the more reactive isomer as that of Ia. The molecular conformation is also illustrated in Fig. 4. The sulfur atom is situated as far as possible from the plane of the benzene ring, the torsion angle C(15)–C(10)–C(9)–S(1) being –93.3°.

An intramolecular non-bonded contact of 2.80 Å between S(1) and O(2) is significantly shorter than the sum, 3.25 Å, of the van der Waals radii (*cf.* Abrahamsson *et al.*[7]) indicating a strong interaction of the negatively polarized carbonyl oxygen with the positively charged sulfur. The oxygen lies along the S–O dipole axis, the O···S–O angle being 173°. In the light of the reaction kinetics presented earlier for this and similar compounds, and the important role of anchimeric assistance in explaining those results, the geometry observed about

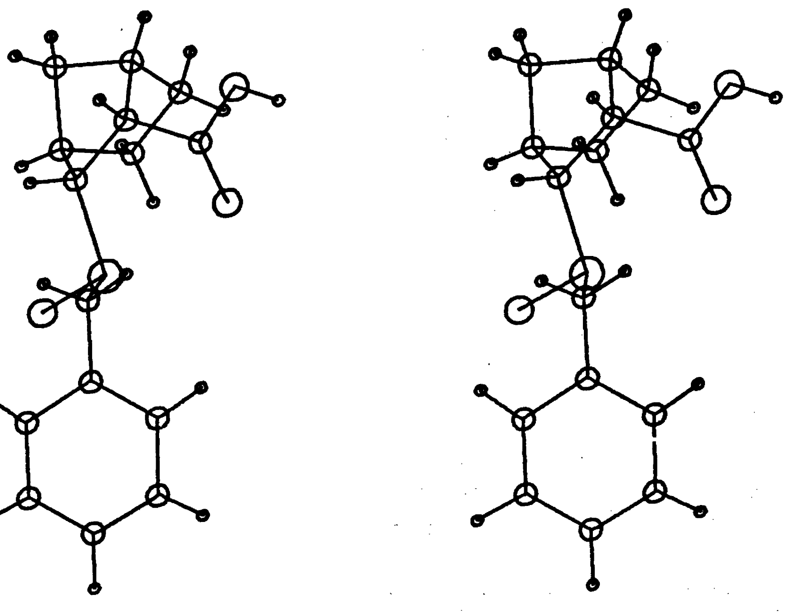


Fig. 4. Stereopair showing the molecular conformation.

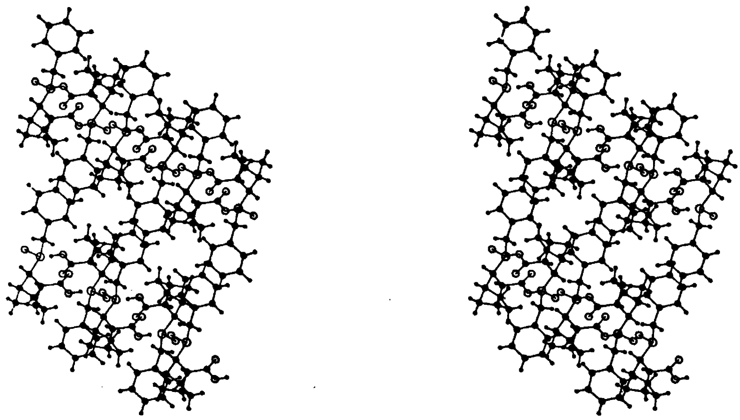


Fig. 5. Molecular packing.

the sulfur atom and especially the spatial relationship between the sulfinyl group and the carbonyl oxygen are consistent with the conclusions arrived at from solution kinetics studies.

The molecular packing is shown in Fig. 5. The O(1)···O(3) contact distance of 2.55 Å, the location of H(16) at a distance of 0.92 Å from O(3) and 1.64 Å from O(1) with an O–H···O angle of 169° indicate the presence of a rather strong hydrogen bond between pairs of molecules. Benzene rings pack in regions both with parallel and perpendicular ring planes whereas in other regions norbornyl rings are in van der Waals contact.

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