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X-Ray and Neutron-Diffraction Study of a Stereoselectively Deuterated Benzyl *t*-Butyl Sulfoxide. A Revised Configuration Assignment for the Chiral Carbon Atom Due to Isotopic Substitution

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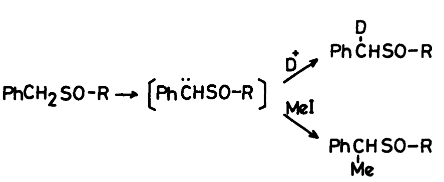
X-Ray analysis of a stereoselectively monodeuterated benzyl *t*-butyl sulfoxide, PhCHDSO–tBu, revealed that the *t*-butyl and phenyl groups are oriented anti to each other in this molecule. Integrated intensities for ten reflections were measured on a two-circle neutron diffractometer and the relative intensity distribution was compared with the calculated neutron structure factors, assuming the atomic parameters obtained by the X-ray analysis. It is concluded that the benzylic hydrogen which is flanked by S–O and *t*-Bu was replaced by deuterium. The results require that the earlier assignment for the relative configuration of PhCHDSO–tBu, should be revised; an important conclusion in view of current discussions of sulfur stereochemistry.

It has been reported that the isotopic exchange and the alkylation of benzyl alkyl sulfoxides, $PhCH_2SO$–Me (**1**) and $PhCH_2SO$–tBu (**2**), proceed via different stereochemical pathways;[1] retention of the configuration for the H–D exchange, and inversion of the configuration for the methylation (Fig. 1). The configuration assignments of the partially deuterated sulfoxides, **1**-*d*[2] and **2**-*d*,[1b] were made by correlating them chemically to optically active benzyl-α-*d* alcohols, the configuration of which has been believed to be established; [(+)-(*S*) and (−)-(*R*)].[3]

The opposite stereochemical outcome for the H–D exchange and the methylation (Fig. 1) is unusual in the current understanding of carbanion chemistry, since electrophilic substitution reactions are more reasonably expected to occur with retention of the intermediate carbanion configuration. In order to examine this point, we prepared crystals of a stereoselectively deuterium-labelled benzyl *t*-butyl sulfoxide (**2**-*d*), and determined the relative disposition of the deuterium atom with respect to the S–O bond by X-ray and neutron diffraction study.

The problem is to know which hydrogen atom (H_{7A} or H_{7B} in Fig. 2) was exchanged by D; it is possible to distinguish the H and D atoms at the benzyl methylene by calculating the structure factors of neutron diffraction which is based on the result of X-ray analysis. Analyses of the crystallographic data revealed that the relative configuration of **2**-*d*, which has been believed to date,[1b,4] should be reversed. This is an important conclusion in view of current discussions of the stereochemistry of sulfoxides.[1,4,5]



1-*d*: R=Me
2-*d*: R=tBu

Fig. 1.

Experimental

Materials. A solution of benzyl *t*-butyl sulfoxide (**2**, 10 mmol) in dry tetrahydrofuran (100 ml) was treated, under nitrogen at −70°, with a hexane solution of butyllithium (12 mmol). After standing for 5 min, the reaction mixture was treated with deuterium oxide (10 ml), and then diluted with water (50 ml). This was neutralized and extracted with ether (200 ml). The ether layer was washed 3 times with water, dried over $MgSO_4$, and then concentrated to give a crude solid of the monodeuterated product. The solid was crystallized from ligroin. This was again crystallized from ligroin solution by slow cooling. A large crystal of approximate dimensions 4×2.5×0.2 mm was chosen for

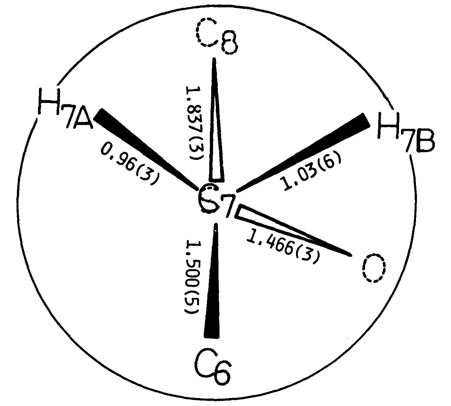


Fig. 2. Newman projection of the compound **2**, viewing along C_7–S axes.

neutron diffraction study. NMR (CCl_4, ppm): 3.64 (1H, s, CHD), 1.25 (9H, s, *t*-Bu), 7.26 (5H, s, Ar).

Crystal Data. Benzyl *t*-butyl sulfoxide, $C_{11}H_{16}OS$, M.W.=196, Partially-deuterated compound, $C_{11}H_{15}DOS$. Monoclinic, Space group $P2_1/n$, $Z=4$. For full hydrogen compound, $a=14.284(7)$, $b=13.185(7)$, $c=6.015(4)$ Å, $\beta=93.83(5)°$, $U=1130$ Å^3, $D_{calcd}=1.1508$ g cm^{-3}, μ for Cu $K\alpha$ radiation 21.8 cm^{-1}.

X-Ray measurement was carried out using a small crystal of the deuterated compound of approximate dimensions 0.2×0.3×0.1 mm. Intensities were measured on a Philips PW1100 diffractometer using graphite monochromated Cu $K\alpha$ radiation. 2543 Reflections were measured within the 2θ range of 6° through 156°. 466 Reflections were below the 2σ(I) level and regarded as unobserved. A total of 2077 reflections were then used for the structure determination.

The structure was determined by the direct method using MULTAN[6)] and refined by the block-diagonal least-squares method to an R value of 0.072. All the 16 hydrogen atoms were found on the difference electron-density map and they were included in the refinement process with isotropic temperature factors.

Results and Discussions

The final atomic parameters are listed in Table 1. The bond lengths and angles are listed in Tables 2 and 3.[7)] The values observed in the present molecule are typical of the related compounds. Some relevant torsional angles are listed in Table 4.

Figure 2 illustrates the orientation of the phenyl group (represented by C_6) to the S–O bond and to the *t*-butyl group (represented by C_8). A stereoview of the molecule is shown in Fig. 3. It is clear that the *t*-butyl group is flanked by the two hydrogen atoms and that the *t*-butyl and the phenyl groups are oriented anti to each other.

It is interesting to compare this conformation with those found in the diastereoisomeric pair of 1-phenylethyl *t*-butyl sulfoxides, [(α *R*, *SS*/*SS*, *SR*)- and (α *R*, *SR*/α *S*, *SS*)-**3**], determined by X-ray methods[8)] (Fig. 4). In both of these compounds, the *t*-butyl group has been shown to be gauche to the phenyl group and anti to the methyl group (Fig. 4d, e). The conformation of **3** has been shown to be maintained in solutions by NMR (LIS),[9)] ORD[8b)] and dipole moment measurements[10)]; the conclusion was supported by molecular force-field calculations[11)].

The conformation of **2** in solution was also studied by various methods. Although the force-field calculations[11)] favored a gauche conformation of *t*-butyl and phenyl groups (Fig. 4c), the energy difference between the anti conformer (Fig. 4a) is small. A dipole moment[10)] study favored the anti conformation. NMR

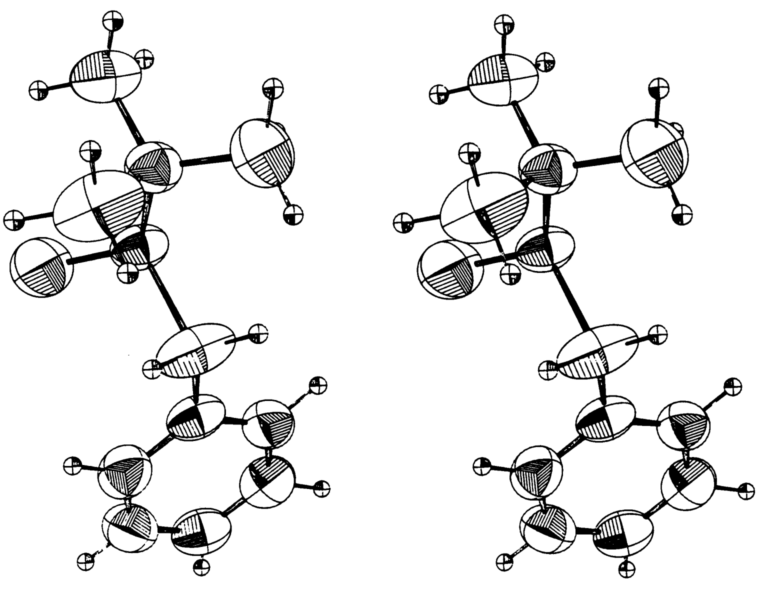
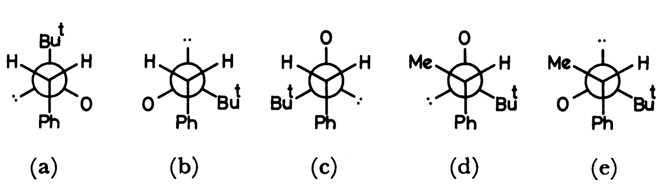


Fig. 3. Stereoview of the molecule **2** drawn by ORTEP.[13)]



(a) (b) (c) (d) (e)

(αS, SR)-**3** (αS,SS)-**3**

Fig. 4. Conformations in solution of the compounds **2** and **3** (one of the enantiomers is illustrated).

Table 1. Final Coordinates of Compound **2** with e.s.d's in Parentheses

Equivalent positions

X	Y	Z
$1/2-X$	$1/2+Y$	$1/2-Z$

and their inverted coordinates

No.	Atom	X 10^5	Y 10^5	Z 10^5	B_{eq} A^2
1	S 1	24300(4)	43270(5)	28960(11)	4.72(.01)
No.	Atom	X 10^4	Y 10^4	Z 10^4	B_{eq} A^2
2	O1	2208(2)	4173(2)	505(4)	7.85(.05)
3	C 1	52(2)	3706(2)	2314(5)	5.76(.04)
4	C 2	−629(2)	2964(3)	2403(5)	6.00(.05)
5	C 3	−716(2)	2424(2)	4316(6)	5.78(.04)
6	C 4	−115(2)	2602(2)	6125(5)	6.04(.05)
7	C 5	575(2)	3338(2)	6061(5)	5.52(.04)
8	C 6	658(2)	3900(2)	4144(5)	4.92(.04)
9	C 7	1369(2)	4737(2)	4115(7)	7.02(.06)
10	C 8	3147(2)	5480(2)	3247(4)	4.75(.04)
11	C 9	2685(3)	6357(3)	1965(7)	7.99(.07)
12	C 10	4060(2)	5217(3)	2234(6)	6.34(.05)
13	C 11	3290(3)	5716(4)	5704(7)	8.93(.08)
No.	Atom	X 10^3	Y 10^3	Z 10^3	B_{eq} A^2
14	H 1	14(2)	407(2)	104(4)	5.5(0.6)
15	H2	−102(2)	289(2)	121(5)	5.7(0.6)
16	H3	−118(2)	196(2)	433(5)	6.1(0.6)
17	H4	−22(2)	224(2)	767(5)	6.4(0.7)
18	H5	101(2)	346(2)	736(4)	5.6(0.6)
19	H7A	155(2)	501(2)	557(5)	6.9(0.7)
20	H7B	118(2)	532(2)	302(5)	7.0(0.7)
21	H9A	206(2)	655(2)	252(5)	6.7(0.7)
22	H9B	313(2)	692(2)	185(5)	7.7(0.8)
23	H9C	256(2)	612(3)	10(5)	8.4(0.8)
24	H10A	432(2)	473(2)	317(4)	5.8(0.6)
25	H10B	394(2)	504(2)	67(4)	5.0(0.5)
26	H10C	450(2)	580(2)	245(5)	5.9(0.6)
27	H11A	357(2)	511(2)	615(5)	6.5(0.6)
28	H11B	384(2)	622(2)	587(5)	6.8(0.7)
29	H11C	268(2)	602(2)	625(5)	6.3(0.6)

$T=\exp\{-2\pi^2(U_{11}h^2a^{*2}+U_{22}k^2b^{*2}+U_{33}l^2c^{*2}+2U_{12}hka^*b^*+2U_{13}hla^*c^*+2U_{23}klb^*c^*)\}$

U_{ij}'s are multiplied by 10^5

No.	Atom	U_{11}	U_{22}	U_{33}	U_{12}	U_{13}	U_{23}
1	S 1	4993(33)	5291(34)	7758(43)	−29(22)	1307(30)	−1050(26)

U_{ij}'s are multiplied by 10^4

1	Atom	U_{11}	U_{22}	U_{33}	U_{12}	U_{13}	U_{23}
2	O1	854(16)	1251(20)	876(16)	−248(14)	56(12)	−413(14)
3	C 1	751(17)	757(17)	692(15)	57(14)	126(13)	136(13)
4	C 2	628(16)	846(19)	796(17)	19(14)	−48(13)	−92(15)
5	C 3	607(15)	599(14)	1004(20)	−29(12)	156(14)	−44(14)
6	C 4	803(19)	687(17)	819(18)	105(14)	156(15)	128(14)
7	C 5	617(15)	775(17)	703(15)	86(13)	26(12)	−72(13)
8	C 6	514(12)	528(12)	845(17)	38(10)	191(12)	−76(11)
9	C 7	669(17)	608(16)	1438(30)	−105(14)	425(19)	−257(18)
10	C 8	545(13)	590(13)	668(14)	−57(10)	35(10)	−84(11)
11	C 9	916(24)	661(19)	1495(36)	133(16)	347(23)	265(20)
12	C 10	556(15)	837(20)	1027(22)	−76(14)	126(14)	−52(17)
13	C 11	998(29)	1533(39)	856(23)	−295(26)	22(20)	−437(23)

Table 1. Continued

	U_{ij}'s are multiplied by 10^3	
No.	Atom	U_{11}
14	H1	70(7)
15	H2	72(8)
16	H3	77(8)
17	H4	81(8)
18	H5	70(8)
19	H7A	87(8)
20	H7B	89(9)
21	H9A	85(8)
22	H9B	97(10)
23	H9C	106(10)
24	H10A	73(8)
25	H10B	63(7)
26	H10C	75(8)
27	H11A	82(8)
28	H11B	86(9)
29	H11C	79(8)

Table 2. Bond Lengths (l/Å)

S1	-O1	1.466(2)
S1	-C7	1.810(4)
S1	-C8	1.837(3)
C1	-C2	1.383(5)
C1	-C6	1.378(4)
C2	-C3	1.366(5)
C3	-C4	1.361(4)
C4	-C5	1.386(4)
C5	-C6	1.382(4)
C6	-C7	1.501(4)
C8	-C9	1.516(5)
C8	-C10	1.516(4)
C8	-C11	1.511(5)
C1	-H1	0.920(26)
C2	-H2	0.887(27)
C3	-H3	0.911(29)
C4	-H4	1.064(30)
C5	-H5	0.980(26)
C7	-H7A	0.964(29)
C7	-H7B	1.033(31)
C9	-H9A	1.002(32)
C9	-H9B	0.983(32)
C9	-H9C	1.166(31)
C10	-H10A	0.912(27)
C10	-H10B	0.973(23)
C10	-H10C	0.994(29)
C11	-H11A	0.923(31)
C11	-H11B	1.027(32)
C11	-H11C	1.035(31)

Table 3. Bond Angles (ϕ/°)

O1	-S1	-C7	107.9(2)
O1	-S1	-C8	108.0(1)
C7	-S1	-C8	100.5(1)
C2	-C1	-C6	120.4(3)
C3	-C2	-C1	120.3(3)
C4	-C3	-C2	119.7(3)
C5	-C4	-C3	120.7(3)
C6	-C5	-C4	120.0(3)
C7	-C6	-C1	121.1(3)
C7	-C6	-C5	120.0(3)
C1	-C6	-C5	118.8(3)
C9	-C8	-S1	110.6(2)
C9	-C8	-C10	109.1(3)
C9	-C8	-C11	111.5(3)
S1	-C8	-C10	104.6(2)
S1	-C8	-C11	108.7(2)
C10	-C8	-C11	112.1(3)
S1	-C7	-C6	111.8(2)

and mechanistic considerations[4b] suggested that this compound takes a folded conformation (Fig. 4b); this conclusion rests, however, on the configuration assignments of the monodeuterated benzyl *t*-butyl sulfoxides ($\alpha R, SS/\alpha S, SR$)- and ($\alpha R, SR/\alpha S, SS$)-**2**-*d*,[1b,4] which is correlated chemically to the optically active benzyl-α-*d* alcohol.[3]

To identify which benzyl hydrogen atom (H_{7A} or H_{7B}) is replaced by deuterium atom, two sets of neutron structure factors were calculated assuming the atomic parameters listed in Table 1; $F_A(hkl)$ based on the model A, in which only H_{7A} is exchanged by D, and $F_B(hkl)$ for model B in which only H_{7B} is exchanged by D. Since the crystal is flattened on (010) plane and it is easier to measure the $h0l$ reflection intensities, ten $h0l$ reflections were chosen having the largest $|F_A|$or$|F_B|$ and the largest $||F_A|-|F_B||$ values. The values are listed in Table 5. Neutron scattering lengths b were taken from the International Tables for X-ray Crystallography III.[12] They were S 0.310, C 0.661, N 0.935, O 0.578, H −0.378, D 0.650 (10^{-12} cm). Integrated intensities for the ten $h0l$ reflections were measured on a two-circle neutron diffractometer at the Japan Atomic Energy Research Institute in Tokai (JAERI). The primary beam was monochromated by a crystal monochromator giving radiation of wavelength 2.338 Å. The observed $|F(h0l)|$ values are normalized to $|F(101)|$ and are listed in Table 5. Inspection of the Table shows that the H–D exchange took place on H_{7B}; the hydrogen atom flanked by S–O and the *t*-butyl groups.

From the above results, we conclude that the configuration assignment of the stereoselectively deuterated sulfoxide (**2**-*d*), reported by Durst et al.,[1b] is in error.

In view of the revised assignment, the paradoxes in the sulfoxide stereochemistry may well be understood. Thus, as expected, the stereochemical pathways for the H–D exchange and the methylation of **2** are the same. A gauche conformation was suggested for **2** (Fig. 4b) by LIS measurements and mechanistic con-

Table 4. Dihedral Angles

Atom 1	=(D1)=Atom 2	=(D2)=Atom 3	=(D3)=Atom 4	Tau (STD)
O1	=1.466=S1	=1.810=C7	=1.501=C6	69.72(15)
O1	=1.466=S1	=1.837=C8	=1.516=C9	50.95(20)
O1	=1.466=S1	=1.837=C8	=1.516=C10	−66.38(17)
O1	=1.466=S1	=1.837=C8	=1.511=C11	173.62(18)
C7	=1.810=S1	=1.837=C8	=1.516=C9	−61.89(19)
C7	=1.810=S1	=1.837=C8	=1.516=C10	−179.28(15)
C7	=1.810=S1	=1.837=C8	=1.511=C11	60.83(21)
C2	=1.383=C1	=1.378=C6	=1.501=C7	−176.83(20)
C2	=1.383=C1	=1.378=C6	=1.382=C5	0.65(39)
C6	=1.501=C7	=1.810=S1	=1.837=C8	−177.31(21)
C3	=1.366=C2	=1.383=C1	=1.378=C6	1.03(40)
C4	=1.361=C3	=1.366=C2	=1.383=C1	−1.63(40)
C5	=1.386=C4	=1.361=C3	=1.366=C2	1.26(41)
C6	=1.382=C5	=1.386=C4	=1.361=C3	−0.59(38)
C7	=1.501=C6	=1.382=C5	=1.386=C4	176.47(16)
C1	=1.378=C6	=1.382=C5	=1.386=C4	−0.88(35)
S1	=1.810=C7	=1.501=C6	=1.378=C1	−84.78(23)
S1	=1.810=C7	=1.501=C6	=1.382=C5	98.10(20)

Table 5. The Calculated and Observed Values of Structure Factors in Neutron Diffraction, with e.s.d's in Parentheses

	Calculated		Observed
(hkl)	$\lvert F_A \rvert$	$\lvert F_B \rvert$	$\lvert F_o \rvert$
101	100	100	100(8.0)
$\bar{7}01$	61	52	54(7.2)
$\bar{8}02$	53	59	61(7.9)
$\bar{4}02$	40	4	9(3.2)
$\bar{3}01$	66	54	73(7.5)
$\bar{1}01$	39	5	7(2.4)
301	1	34	33(5.1)
501	45	62	60(7.3)
701	53	65	50(7.8)
$\bar{2}02$	28	4	0(2.4)

siderations.[4b)] With the revised assignment, the solution conformation of **2** is concluded as *t*-Bu/Ph anti (Fig. 4a); this is the conformation found in crystals and is compatible with the results obtained by dipole moment measurements.[10)] The alcoholic analogue of **2**, (PhCH$_2$CHOH-tBu),[14)] has been shown to have the *t*-Bu/Ph anti conformation in solutions. This, again, is consistent with the above conclusion regarding the solution conformation of **2**.

A question remains, however, as to the origin of the erroneous configuration assignment of **2**-*d*. At present, we do not know whether this arose from the chemical correlation process,[1b)] or originated from the absolute configuration assignment of optically active benzyl alcohol.[3)]

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