

The Crystal Structures of Methyl 1,5-Dithio- α -D-ribofuranoside Quarterhydrate and Methyl 1,5-Dithio- β -D-ribofuranoside

BY R. L. GIRLING* AND G. A. JEFFREY

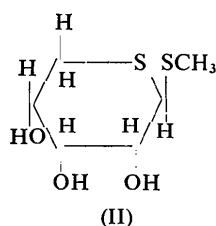
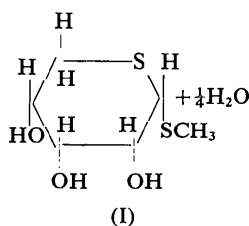
Department of Crystallography, University of Pittsburgh, Pittsburgh, Pennsylvania 15260, U.S.A.

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The crystal structures of methyl 1,5-dithio- α -D-ribofuranoside, $C_6H_{12}O_3S_2 \cdot \frac{1}{4}H_2O$, and methyl 1,5-dithio- β -D-ribofuranoside, $C_6H_{12}O_3S_2$, have been determined from Cu $K\alpha$ data and refined to R values of 0.03 and 0.05 respectively. The crystal data are, respectively; space group $C2$, $Z=8$, $a=29.79$ (2), $b=5.606$ (4), $c=11.45$ (2) Å, $\beta=107.78$ (2)°; space group $P2_1$, $Z=4$, $a=7.779$ (5), $b=24.40$ (1), $c=5.232$ (4) Å, $\beta=116.19$ (2)°. The α pyranoside molecules have the 1C_4 ring conformation, which is stabilized by syn-axial O(H)···O intramolecular hydrogen bonds. The two symmetry-independent molecules differ, both in the donor-acceptor direction of their intramolecular hydrogen bonds and in the conformation about the thio-glycosidic bonds. The β pyranoside molecules have the 4C_1 ring conformation with no significant differences between the two molecules. The molecular packing in both structures shows well defined separation into hydrogen bonded columns which cohere by van der Waals interactions, rather than the three-dimensional hydrogen bonding more commonly found in carbohydrate crystal structures.

Introduction

This work forms part of the crystal structural investigations of some methyl thio-ribofuranosides, which have hitherto included methyl 1-thio- α -ribofuranoside (Girling and Jeffrey, 1973a) and methyl 5-thio- α - and β -ribofuranosides (Girling & Jeffrey, 1973b). The compounds, methyl 1,5-dithio- α -ribofuranoside quarterhydrate (I) and methyl 1,5-dithio- β -ribofuranoside (II) differ from those previously studied in that they have sulfur atoms in both the ring and glycosidic position. They were provided by Professor N. A. Hughes of the University of Newcastle-on-Tyne, England, who has studied the conformational equilibria in solution by n.m.r. spectroscopy (Hughes, 1973).



Crystal data

(I)

Methyl 1,5-dithio- α -D-ribofuranoside quarterhydrate,
 $C_6H_{12}O_3S_2 \cdot \frac{1}{4}H_2O$
 m.p. 63–5°C
 M.W. 205.2

Monoclinic, space group $C2$, from systematic extinctions $h+k$ odd; missing for hkl and structure solution

$a=29.79$ (2), $b=5.606$ (4),
 $c=11.45$ (2) Å, $\beta=107.78$ (2)°
 $Z=8$
 $D_m=1.485$, $D_x=1.457$ g cm $^{-3}$
 μ (Cu $K\alpha$) = 50.5 cm $^{-1}$

(II)

Methyl 1,5-dithio- β -D-ribofuranoside, $C_6H_{12}O_3S_2$
 m.p. 111–3°C
 M.W. 196.3

Monoclinic, space group $P2_1$, from extinction k odd;
 missing for $0k0$ and structure solution
 $a=7.779$ (5), $b=24.40$ (1),
 $c=5.232$ (4) Å, $\beta=116.19$ (2)°
 $Z=4$
 $D_m=1.473$, $D_x=1.464$ g cm $^{-3}$
 μ (Cu $K\alpha$) = 51.2 cm $^{-1}$

Intensity data

For (I) three data sets were measured on a FACS-I with a θ - 2θ scan of 1° min $^{-1}$. A crystal, 0.05 × 0.09 × 0.45 mm from the original specimen gave 1535 observed reflections out of 1700 measured with Cu $K\alpha$ radiation to 2θ max of 126°. The same crystal gave 520 observed out of 1021 measured reflections with Mo $K\alpha$ radiation to 2θ max of 52°. A crystal, 0.04 × 0.08 × 0.42 mm, recrystallized from ethyl alcohol, gave 1351 observed reflections out of 1700 with Cu $K\alpha$ radiation. Absorption corrections and a decomposition correction were applied to the Cu $K\alpha$ data.

For (II) a crystal, 0.07 × 0.60 × 0.05 mm, recrystallized from ethyl alcohol gave 1092 observed intensities

* Present address: Division of Biological and Medical Research, Argonne National Laboratory, Argonne, Illinois 60440, U.S.A.

out of 1337 measured with Cu $K\alpha$ radiation to $2\theta_{\max}$ 120° on a CAD-3 with θ - 2θ scan at $6^\circ/\text{min}$.

Structure determination and refinement

The structure of (I) was solved by a combination of direct and Patterson superposition methods. Using the appropriate parts of X-RAY 67 (Stewart, 1967), a solution for the ($h0l$) projection was obtained by symbolic addition. The y coordinates were then obtained from the Patterson synthesis by superposition using an IBM 1130 program written by Seeman (1970). The water molecules lie in special positions on the twofold axes, and there are two symmetry-independent carbohydrate molecules in general positions, corresponding to a one-quarter hydrate. The structure of (II) was solved directly from the Patterson synthesis. Refinement by

block-diagonal least-squares calculations (Shiono, 1970) on both structures reduced the R values to 0.06. The hydrogen atoms were then located on difference syntheses for (I), but not unambiguously for (II). Anomalous dispersion corrections were made and the final refinement by the full-matrix least-squares method with anisotropic temperature factors for C, S and O and isotropic factors for hydrogen gave R and wR values of 0.032, 0.031 for (I) and 0.049 and 0.028 for (II), where $w = 1/\sigma(F^2)$. Refinement of the $+h+k+l$ reflections for the D and L isomers rejected the L at greater than 99.9% confidence level (Hamilton, 1965). The positional parameters obtained for (I) from the separate refinement of two sets of Cu $K\alpha$ and Mo $K\alpha$ data differed by less than 1.7 standard deviations, with no temperature factor refinement with the Mo $K\alpha$ data. The atomic positional and thermal parameters listed

Table 1. Atomic parameters with their e.s.d.'s

The positional parameters are expressed as fractions of the lattice translations. The thermal parameters are defined by the expression $T = \exp[-(h^2\beta_{11} + k^2\beta_{22} + l^2\beta_{33} + 2hk\beta_{12} + 2hl\beta_{13} + 2kl\beta_{23})]$. All β_{ij} 's, positional parameters and their e.s.d.'s which follow in parentheses have been multiplied by 10^4 for heavy atoms and by 10^2 for hydrogen atoms.

(a) Methyl 1,5-dithio- α -D-ribofuranoside

	Molecule A									
	x	y	z	β_{11}	β_{22}	β_{33}	β_{12}	β_{13}	β_{23}	
S(1)	2912.2 (4)	4890 (10)	4584 (1)	9.8 (1)	296 (10)	93 (1)	17 (1)	6.0 (3)	12 (2)	
S(5)	3374.5 (4)	3200*	7018 (1)	12.4 (2)	314 (10)	71 (1)	10 (1)	16.0 (3)	-1 (2)	
C(1)	3245 (1)	2465 (10)	5413 (4)	6.6 (5)	231 (20)	68 (4)	5 (2)	7 (3)	5 (7)	
C(2)	3693 (1)	1949 (10)	5065 (4)	6.4 (5)	199 (10)	55 (4)	2 (2)	7 (1)	4 (7)	
C(3)	3965 (1)	-165 (10)	5800 (3)	6.8 (2)	165 (10)	60 (4)	-3 (2)	7 (1)	-9 (7)	
C(5)	3724 (2)	700 (10)	7681 (4)	12.8 (7)	302 (20)	68 (4)	4 (3)	14 (1)	40 (8)	
C(6)	2630 (2)	3558 (10)	3162 (5)	13.8 (8)	488 (30)	84 (5)	10 (5)	1 (2)	1 (11)	
O(2)	3989 (1)	3966 (10)	5284 (4)	9.1 (5)	208 (10)	55 (4)	-6 (2)	9 (1)	22 (5)	
O(3)	4346 (1)	-610 (10)	5324 (3)	7.9 (4)	230 (10)	68 (3)	17 (2)	9 (1)	15 (5)	
O(4)	4473 (1)	2140 (10)	7511 (3)	10.2 (5)	291 (10)	60 (3)	-8 (3)	2 (1)	7 (6)	
O(W)	5000*	2789 (10)	5000*	7.2 (6)	320 (20)	94 (5)	0*	11 (2)	0*	

	Molecule B									
	x	y	z	β_{11}	β_{22}	β_{33}	β_{12}	β_{13}	β_{23}	
S(1)	3215.5 (4)	8206 (10)	1734 (1)	11.2 (2)	487 (10)	99 (1)	14 (1)	12.3 (4)	-1 (3)	
S(5)	3677.1 (4)	5913 (10)	95 (1)	10.1 (1)	374 (10)	53 (1)	2 (1)	3.0 (3)	-18 (2)	
C(1)	3766 (2)	8008 (10)	1390 (4)	9.8 (6)	318 (20)	58 (4)	10 (3)	5 (1)	4 (8)	
C(2)	4149 (2)	7086 (10)	2515 (4)	8.9 (6)	301 (20)	58 (4)	1 (3)	5 (1)	-13 (8)	
C(3)	4625 (2)	7000 (10)	2260 (4)	8.7 (5)	189 (20)	65 (4)	-7 (3)	3 (1)	19 (7)	
C(4)	4635 (2)	5427 (10)	1182 (4)	8.8 (6)	279 (60)	67 (4)	4 (3)	8 (1)	26 (7)	
C(5)	4271 (2)	6168 (10)	10 (4)	11.6 (6)	351 (20)	53 (4)	6 (3)	10 (1)	6 (9)	
C(6)	2915 (2)	373 (20)	534 (7)	12.7 (9)	505 (40)	148 (8)	23 (5)	-3 (2)	14 (14)	
O(2)	4033 (1)	4796 (10)	2918 (3)	11.5 (5)	354 (20)	65 (3)	-7 (3)	11 (1)	40 (7)	
O(3)	4572 (1)	2963 (10)	1421 (4)	10.7 (6)	234 (10)	96 (4)	5 (3)	4 (1)	2 (6)	

Hydrogen parameters

	Molecule A				Molecule B			
	x	y	z	B	x	y	z	B
H(2)	40.0 (2)	43 (1)	49 (1)	1 (1)	40.5 (2)	40 (1)	25 (1)	3 (1)
H(3)	45.0 (1)	-12 (1)	56 (1)	0 (1)	49.3 (1)	55 (1)	37 (1)	2 (1)
H(4)	43.9 (2)	31 (1)	72 (1)	1 (1)	47.8 (1)	27 (1)	17 (1)	2 (1)
H(5)	29.9 (1)	11 (1)	52 (1)	3 (1)	37.9 (1)	99 (1)	12 (1)	1 (1)
H(6)	36.1 (1)	14 (1)	41 (1)	3 (1)	42.0 (1)	84 (1)	32 (1)	3 (1)
H(7)	37.2 (1)	-16 (1)	56 (1)	1 (1)	46.9 (1)	87 (1)	22 (1)	2 (1)
H(8)	43.4 (2)	-15 (1)	75 (1)	5 (1)	49.6 (1)	55 (1)	11 (1)	4 (1)
H(9)	38.6 (2)	11 (1)	86 (1)	6 (1)	43.1 (1)	77 (1)	-2 (1)	2 (1)
H(10)	34.8 (2)	-8 (1)	74 (1)	4 (1)	42.8 (1)	53 (1)	-6 (1)	2 (1)
H(11)	24.2 (2)	23 (1)	31 (1)	6 (1)	28.5 (2)	93 (2)	-3 (1)	10 (2)
H(12)	28.5 (2)	29 (1)	28 (1)	5 (1)	30.7 (2)	21 (1)	7 (1)	7 (2)
H(13)	24.0 (2)	44 (1)	27 (1)	5 (1)	26.0 (2)	5 (1)	6 (1)	8 (2)
H(W)	51.8 (1)	20 (1)	50 (1)	1 (1)				

Table 1 (cont.)

(b) Methyl 1,5-dithio- β -D-ribofuranoside

	Molecule A			Molecule B						
	x	y	z	β_{11}	β_{22}	β_{33}	β_{12}	β_{13}	β_{23}	
S(1)	1258 (3)	-26 (2)	3891 (1)	152 (1)	20 (1)	524 (1)	-7 (2)	116 (1)	0 (3)	
S(5)	-2898 (3)	0*	753 (1)	150 (1)	20 (1)	367 (1)	0 (2)	58 (1)	-27 (3)	
C(1)	-809 (12)	403 (4)	3085 (2)	137 (2)	15 (2)	396 (5)	-10 (5)	120 (2)	12 (8)	
C(2)	-1027 (10)	618 (4)	5705 (2)	41 (2)	14 (2)	217 (4)	-2 (4)	-17 (2)	-13 (7)	
C(3)	-2845 (10)	954 (4)	4899 (2)	69 (1)	19 (2)	302 (4)	-7 (4)	67 (2)	-20 (8)	
C(4)	-4662 (13)	649 (4)	3183 (2)	123 (2)	18 (2)	303 (5)	-3 (6)	65 (3)	0 (9)	
C(5)	-4759 (14)	477 (5)	357 (2)	118 (2)	20 (3)	363 (5)	-2 (6)	64 (3)	-21 (10)	
C(6)	925 (20)	-556 (6)	5956 (2)	211 (4)	21 (3)	1094 (9)	16 (9)	173 (5)	20 (15)	
O(2)	619 (9)	922 (3)	7505 (1)	118 (1)	19 (1)	272 (3)	0 (4)	-4 (2)	1 (6)	
O(3)	-2733 (8)	1447 (3)	3575 (1)	126 (1)	15 (1)	485 (4)	-14 (3)	137 (2)	24 (6)	
O(4)	-6215 (8)	1000 (3)	2833 (1)	90 (1)	22 (2)	388 (4)	4 (4)	29 (2)	0 (6)	
Molecule B										
S(1)	-5860 (4)	-1697 (2)	948 (1)	195 (1)	22 (1)	539 (2)	7 (2)	47 (1)	26 (3)	
S(5)	-1740 (3)	-1850 (1)	3030 (1)	188 (1)	19 (1)	423 (1)	-6 (1)	135 (1)	3 (2)	
C(1)	-3923 (14)	-2176 (5)	2553 (2)	193 (2)	19 (2)	240 (6)	23 (6)	96 (3)	-1 (9)	
C(2)	-3800 (13)	-2450 (4)	5285 (2)	149 (2)	14 (2)	408 (6)	9 (5)	129 (3)	-20 (3)	
C(3)	-2156 (14)	-2826 (4)	6692 (2)	140 (2)	11 (2)	340 (6)	-5 (5)	124 (3)	6 (8)	
C(4)	-206 (12)	-2556 (4)	7648 (2)	129 (2)	19 (2)	247 (5)	14 (5)	33 (3)	-11 (8)	
C(5)	67 (17)	-2367 (4)	4974 (2)	174 (2)	15 (2)	429 (6)	1 (6)	*125 (3)	11 (10)	
C(6)	-5314 (27)	-1190 (6)	3649 (2)	459 (5)	18 (3)	863 (10)	46 (11)	371 (6)	38 (14)	
O(2)	-5509 (9)	-2735 (3)	4813 (1)	96 (1)	20 (2)	481 (4)	2 (4)	57 (2)	22 (6)	
O(3)	-2232 (9)	-3275 (3)	4875 (1)	168 (2)	12 (1)	394 (3)	1 (3)	112 (2)	-5 (6)	
O(4)	1314 (12)	-2907 (4)	9415 (2)	119 (2)	25 (2)	442 (5)	0 (4)	74 (2)	-7 (7)	

Hydrogen parameters

	Molecule A				Molecule B			
	x	y	z	B	x	y	z	B
H(2)	9 (1)	12 (3)	66 (2)	2	-63 (1)	-25 (3)	43 (2)	2
H(3)	-23 (1)	15 (4)	29 (2)	2	-29 (1)	-35 (4)	55 (2)	2
H(4)	-69 (1)	9 (4)	18 (2)	2	19 (2)	-29 (6)	89 (3)	2
H(5)	-7 (1)	8 (4)	21 (2)	3	-42 (1)	-25 (4)	14 (2)	3
H(6)	-11 (1)	3 (4)	68 (2)	3	-36 (1)	-22 (4)	67 (2)	3
H(7)	-30 (1)	11 (4)	64 (2)	3	-21 (1)	-29 (4)	83 (2)	3
H(8)	-50 (1)	3 (3)	43 (2)	3	-3 (1)	-22 (4)	88 (2)	3
H(9)	-46 (1)	8 (4)	-1 (2)	3	11 (1)	-22 (4)	51 (2)	3
H(10)	-56 (1)	2 (3)	-3 (2)	3	-1 (1)	-28 (4)	37 (2)	3
H(11)	-1 (1)	-6 (4)	62 (2)	3	-42 (1)	-9 (4)	36 (2)	3
H(12)	12 (1)	-4 (4)	84 (2)	3	-43 (1)	-12 (4)	57 (2)	3
H(13)	20 (1)	-8 (4)	66 (2)	3	-64 (1)	-9 (4)	27 (2)	3

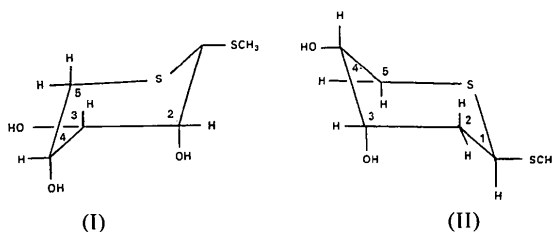
* These coordinates were used to fix the origin.

in Table 1 and the structure factors in Table 2* are from a weighted average of all three data sets for (I), with weights determined by counting statistics (Shiono, 1970). The thermal ellipsoids and atomic numbering for the two pairs of symmetry-independent molecules (IA) and (IB), (IIA) and (IIB), are given in Figs. 1 and 2.

Results and discussion

A primary objective of this work was to determine the ring conformation of these molecules in the solid state. Previous work by Girling & Jeffrey (1973b) has shown that the α and β methyl 5-thio-ribofuranosides have the same ring conformation, *i.e.*, the normal 4C_1 . In con-

trast, the α and β -methyl 1,5-dithio-ribofuranosides have different conformations; the alternate 1C_4 in the α derivative, (I), and the normal 4C_1 in the β compound, (II). The thio-methyl group is thereby equatorial in both anomers.



* This table has been deposited with the British Library Lending Division as Supplementary Publication No. SUP 30228 (22 pp., 1 microfiche). Copies may be obtained through the Executive Secretary, International Union of Crystallography, 13 White Friars, Chester CH1 1NZ, England.

The n.m.r. studies of this series of mono and dithio-ribofuranosides in pyridine solution (after the exchange of hydroxyl hydrogen atoms for deuterium) by Hughes (1973) shows that both the α and β methyl 5-thio and the β methyl 1,5-dithio compounds have a

high proportion of the molecules in the normal 4C_1 conformation, which is that observed in the crystals. The α methyl 1,5-dithio compound also shows a majority of 4C_1 conformers in pyridine solution, but the n.m.r. data does suggest that the alternate 1C_4 content is higher than for the β configuration. The equilibrium composition of these molecules in ethyl alcohol or aqueous solution is unknown, but it is interesting to note that the conformational distinction observed in the solid state is to some degree reflected in the equilibrium composition in the pyridine solution studies.

The 4C_1 conformation, (II), for the β derivatives is that expected, since the alternate 1C_4 would bring the O(3)-H and S(1)CH₃ into a syn-axial orientation, a factor generally associated with conformational instability in the pyranose sugars (Stoddart, 1971). The anomeric effect (Lemieux, 1971) which favors the axial orientation for glycosidic groups, is likely to be less important in these thio derivatives.

For the α compound, both ring conformations involve syn-axial interactions, between O(2)H and O(4)H in the observed 1C_4 , or between O(3)H and S(1)CH₃ in the 4C_1 conformation. Therefore, both on steric or hydrogen-bonding considerations, the observed conformation, (I), would be preferred; *i.e.*, the van der Waals repulsion at about 2.5 Å is less for O...O than for O...S, or an O-H...O hydrogen bond is stronger than an O-H...S. In fact, the O-H...O intramolecular hydrogen bonds are observed in both independent molecules with different donor-acceptor directions, as shown in Fig. 3. That in *IB* is a weak interaction with H...O greater than 2.3 Å; nevertheless, it appears definite since the next closest H...O approach is to a water oxygen at 3.4 Å. This syn-axial intramolecular bonding is formed with no large distortions of the ring torsion angles, since torsion angles of $60 \pm 5^\circ$ are commonly observed in pyranose sugars in which there is no syn-axial intramolecular hydrogen bonding. This is in contrast to the strain effect of the repulsion between syn-axial oxygens in the absence of intramolecular hydrogen bonding, as observed in the structures of methyl 5-thio- α -D-ribofuranoside (Girling & Jeffrey, 1973*b*) and methyl α -D-altropyranoside (Gatehouse & Poppleton, 1971), where separations of 2.99 and 2.94 Å are accompanied by ring torsion angles of about 75° .

The two symmetry-independent α molecules (*IA* and *IB*) also differ in the conformation about the thioglycosidic link, the methyl group being *ap* (*trans*) to the ring sulfur in (*IA*) and *-sc* (*gauche*) in (*IB*). This may be an important difference from the pyranosides, where the *ap/ap* conformation for a C-O-C-O-C bond sequence is believed to be the least favored of the possible staggered bond conformations, because of the anomeric effect (Lemieux, 1971; Jeffrey, Pople & Radom, 1972).

Since the thio-glycosidic link is *+sc* in the β -molecules (*IIA* and *IIB*), all three staggered rotameric conformations are represented in these two crystal structures (see Table 3 which gives the torsion angle data). Except for the difference in α and β configuration and in

the glycosidic conformations, the correspondence is within a few degrees. An analysis of these results together with those from the other 5-thio-ribofuranosides shows a systematic difference in the ring torsion angles when sulfur substitutes for oxygen. The angles about the C-S ring bonds are the smallest torsion angles in the rings, whereas in the pyranose sugars, the corresponding C-O torsion angles are the largest and closest to the ideal 60° value for a cyclohexane chair conformation (*cf.* Arnott & Scott, 1972). The bond distances and angles in the four molecules are shown in Table 4. For the α compound, the C-C and C-O distances are not significantly different from the mean values of 1.526 and 1.424 Å. There appears to be a systematic difference in the C-S bonds in that those in molecule (*IB*) are all greater than the corresponding bonds in (*IA*), by 0.03 to 0.09 Å. Comparable differences in C-S bond lengths have been reported for methyl 1-thio- β -D-xylopyranoside (1.796, 1.823 Å) by Mathieson & Poppleton (1966), for ethyl 1-thio- α -D-glucopyranoside (1.769, 1.808 Å) by Parthasarathy &

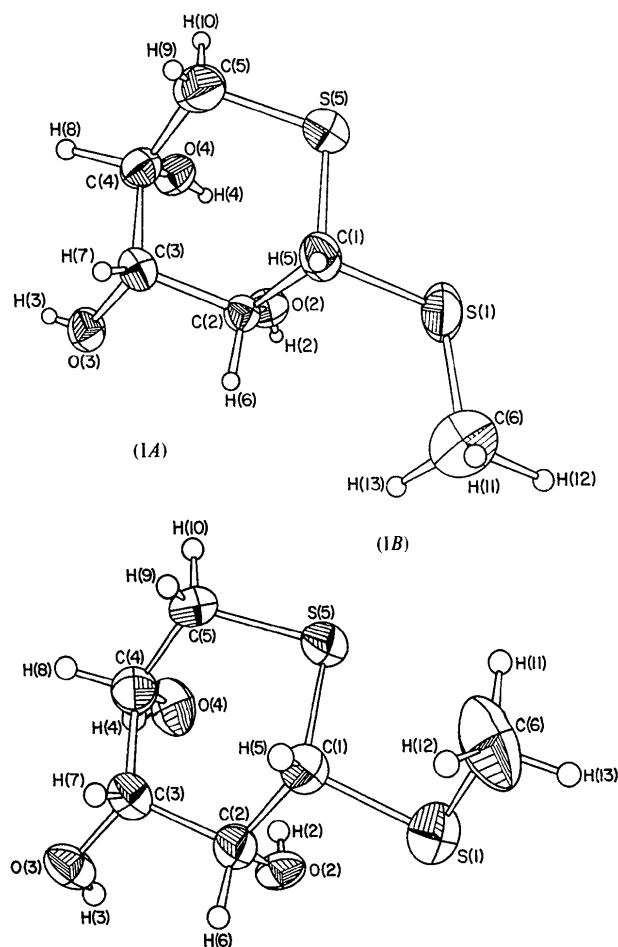
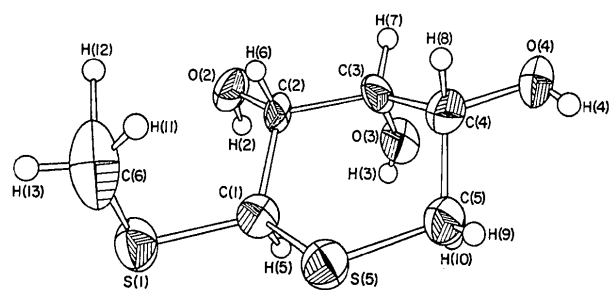


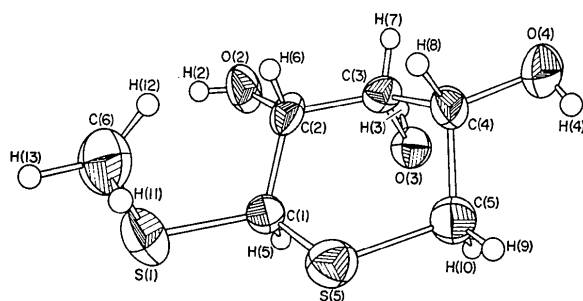
Fig. 1. The two symmetry independent molecules, (*IA*, *IB*), of methyl 1,5-dithio- α -D-ribofuranoside in the crystal structure of the quarterhydrate [ORTEP, at 50% probability level (Johnson, 1965)].

Davis (1967), and for ethyl 2,5-ethyl-1,2-dithio- α -D-mannofuranoside (1.78, 1.83; 1.78, 1.84 Å), (Ducruix & Pascard-Billy, 1972). In the methyl 1-thio- α -

and methyl 5-thio- α -D-ribofuranosides, the molecules with 4C_1 ring conformations have mean C-S bonds 0.015 Å longer than that with 1C_4 (Girling & Jeffrey, 1973a, 1973b). These bond length variations with conformation may be real, since they are the same order of



(IIA)



(IIB)

Fig. 2. The two symmetry independent molecules, (IIA, IIB), of methyl 1,5-dithio- β -D-ribofuranoside in the crystal structure [ORTEP, at 50% probability level (Johnson, 1965)].

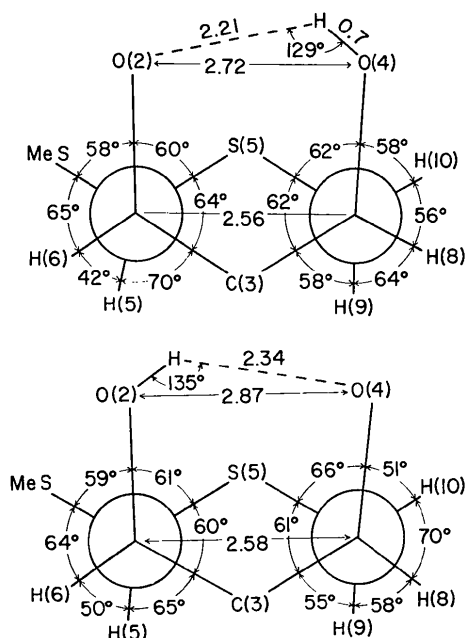


Fig. 3. The intramolecular hydrogen bonding in the two symmetry independent molecules of methyl 1,5-dithio- α -D-ribofuranoside, viewed in the direction of the C(2) \rightarrow C(1) and C(4) \rightarrow C(5) bonds. (IA) is above, (IB) is below.

Table 3. Torsional angles for methyl 1,5-dithio- α -D-ribofuranoside (I), and methyl 1,5-dithio- β -D-ribofuranoside (II)

Ring angles	(IA)	(IB)	(IIA)	(IIB)
S(5)-C(1)-C(2)-C(3)	60.2°	64.4°	56°	52°
C(1)-C(2)-C(3)-C(4)	-62.6	-59.0	-60	-60
C(2)-C(3)-C(4)-C(5)	62.0	57.4	63	67
C(3)-C(4)-C(5)-S(5)	-60.6	-62.0	-64	-63
C(4)-C(5)-S(5)-C(1)	53.6	59.8	56	52
C(5)-S(5)-C(1)-C(2)	-53.3	-61.1	-51	-46
Exocyclic angles				
S(1)-C(1)-C(2)-C(3)	-179.6	-177.7	177	177
S(1)-C(1)-S(5)-C(5)	-177.4	179.8	-177	-175
C(6)-S(1)-C(1)-S(5)	-158.9	-81.5	67	66
C(6)-S(1)-C(1)-C(2)	77.6	158.7	-57	-62
O(2)-C(2)-C(1)-S(1)	59.3	57.8	-58	-58
O(2)-C(2)-C(1)-S(5)	-60.9	-60.1	-179	176
O(2)-C(2)-C(3)-C(4)	59.4	66.3	176	173
O(3)-C(3)-C(2)-C(1)	174.9	176.1	67	61
O(3)-C(3)-C(2)-O(2)	-63.1	-58.6	-57	-65
O(3)-C(3)-C(4)-C(5)	-178.6	-177.0	-63	-58
O(4)-C(4)-C(3)-C(2)	-64.4	-66.0	-175	-170
O(4)-C(4)-C(3)-O(3)	55.0	59.6	59	66
O(4)-C(4)-C(5)-S(5)	66.3	62.4	176	173

Table 4. Bond distances (Å) and angles (°) in methyl 1,5-dithio- α -D-ribofuranoside (I) and methyl 1,5-dithio- β -D-ribofuranoside (II), with estimated standard deviations in parentheses

Bond distances	(IA)	(IB)	(IIA)	(IIB)
S(1)-C(1)	1.777 (6)	1.802 (6)	1.81 (1)	1.80 (1)
S(1)-C(6)	1.755 (8)	1.847 (10)	1.78 (2)	1.78 (2)
S(5)-C(1)	1.807 (5)	1.846 (6)	1.83 (1)	1.79 (1)
S(5)-C(5)	1.772 (6)	1.805 (6)	1.80 (1)	1.83 (1)
C(1)-C(2)	1.530 (7)	1.526 (8)	1.55 (1)	1.54 (1)
C(2)-C(3)	1.533 (7)	1.535 (8)	1.52 (1)	1.48 (1)
C(3)-C(4)	1.529 (7)	1.524 (8)	1.50 (1)	1.52 (1)
C(4)-C(5)	1.530 (7)	1.503 (8)	1.51 (1)	1.57 (1)
C(2)-O(2)	1.409 (6)	1.441 (7)	1.42 (1)	1.42 (1)
C(3)-O(3)	1.424 (6)	1.417 (7)	1.41 (1)	1.44 (1)
C(4)-O(4)	1.408 (6)	1.431 (7)	1.43 (1)	1.42 (1)
H-bonds				
O(2)-O(4)	2.717	2.871		
O(2)-H(4)	2.21	-		
O(4)-H(2)	-	2.34		
O(W)-O(3)	2.829	2.745		
O(W)-H(3)	2.15	2.11		
O(2A)-O(2B)		2.791		
H(2A)-O(2B)		2.28		
O(4A)-O(4B)		2.771		
O(4A)-H(4B)		2.17		
O(3A)-O(3B)		2.727		
O(3B)-H(3A)		2.14		
O(2A)-O(3B)			2.89	
O(3A)-O(4B)			2.77	
O(3B)-O(4A)			2.70	
O(4A)-O(2A)			2.79	
O(2B)-O(3A)			2.75	

Table 4 (cont.)

Bond angles				
C(1)—S(1)—C(6)	101.6 (3)	98.3 (3)	102 (1)	103 (1)
C(1)—S(5)—C(5)	99.8 (2)	95.1 (3)	99 (1)	103 (1)
S(1)—C(1)—C(2)	113.2 (3)	109.4 (4)	115 (1)	114 (1)
S(5)—C(1)—C(2)	112.1 (3)	110.4 (4)	111 (1)	113 (1)
C(1)—C(2)—C(3)	111.1 (4)	110.3 (4)	113 (1)	115 (1)
C(2)—C(3)—C(4)	113.3 (4)	114.8 (4)	114 (1)	114 (1)
C(3)—C(4)—C(5)	110.7 (4)	112.1 (4)	111 (1)	110 (1)
C(4)—C(5)—S(5)	113.3 (1)	112.4 (3)	112 (1)	109 (1)
C(1)—C(2)—O(2)	110.5 (4)	112.4 (4)	110 (1)	112 (1)
C(3)—C(2)—O(2)	109.0 (4)	111.0 (4)	111 (1)	109 (1)
C(2)—C(3)—O(3)	105.9 (4)	111.0 (4)	110 (1)	112 (1)
C(4)—C(3)—O(3)	111.5 (4)	109.6 (4)	112 (1)	107 (1)
C(3)—C(4)—O(4)	112.8 (4)	111.5 (4)	107 (1)	112 (1)
C(5)—C(4)—O(4)	112.0 (4)	110.0 (4)	112 (1)	111 (1)

H-bond angles

O(3)—H—O(W)	165	160
O(2)—H—O(4)	129	135
O(2A)—H—O(2B)	163	
O(4B)—H—O(4A)	175	
O(3B)—H—O(3A)	175	

magnitude as observed and predicted theoretically for the C—O bonds of pyranosides (Jeffrey, Pople & Radom 1972). The data for the β compound (IIA and IIB) are not sufficiently accurate to permit similar detailed comparison.

The hydrogen bonding in the methyl 1,5-dithio- α -D-ribofuranose quarterhydrate is shown in Fig. 4, and the numerical data are given in Table 4. The hydrogen bonds link the molecules in columns which extend in the *c* direction with the tetrahedrally coordinated water molecules on twofold axes in the center of the column. The circumference of the columns is formed by the cyclic hydrogen-bonded sequence O(2A)—H...O(2B)—H...O(4B)—H...O(4A)—H...O(2A)—H... which includes alternating intra- and intermolecular hydrogen bonds. In the direction of the column axis, the molecules are linked through infinite chains which include the water molecules, *i.e.*, O(3A)—H...O(W)—H...O(3B)—H...O(3A)—H... The water molecules thereby lie at the center of the column, each surrounded

by four carbohydrate molecules, which are so oriented that their hydroxyls form the inner core of the column and the hydrophobic parts of the molecules, *i.e.*, C(5)H₂, S(5), C(1)—S(1)—C(6)H₃, form the outer core. There is no hydrogen bonding between the columns, which cohere by van der Waals interactions. The structure therefore provides an especially clear example of a segregation into regions of hydrophilic and hydrophobic molecular cohesion. All intermolecular O...O distances not involved in hydrogen bonding are greater than 3.19 Å, all C...O or C...C distances are greater than 3.2 Å. The molecular packing is shown in Fig. 5.

The hydrogen-bond scheme for the β derivative is less well-determined because of the poorer definition

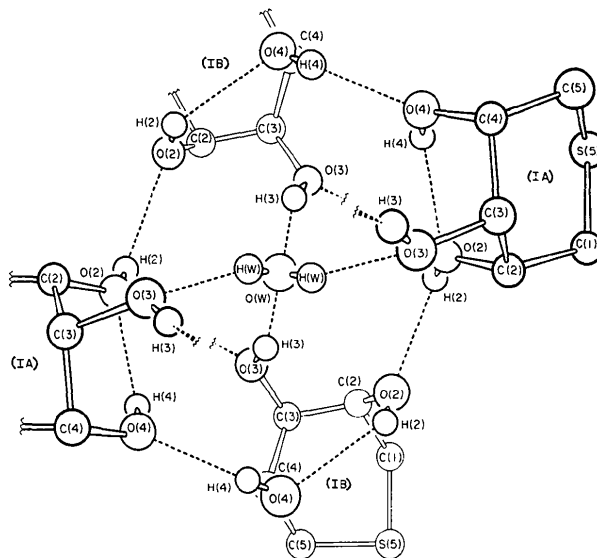


Fig. 4. Hydrogen bonding in methyl 1,5-dithio- α -D-ribofuranose quarterhydrate, viewed down the *b* axis, showing the cross section of the hydrogen-bonded column of molecules. (The hydrogens attached to C(5) and the hydrogen and S—CH₃ attached to C(1) which are not involved in the hydrogen bonding are omitted to clarify the illustration.)

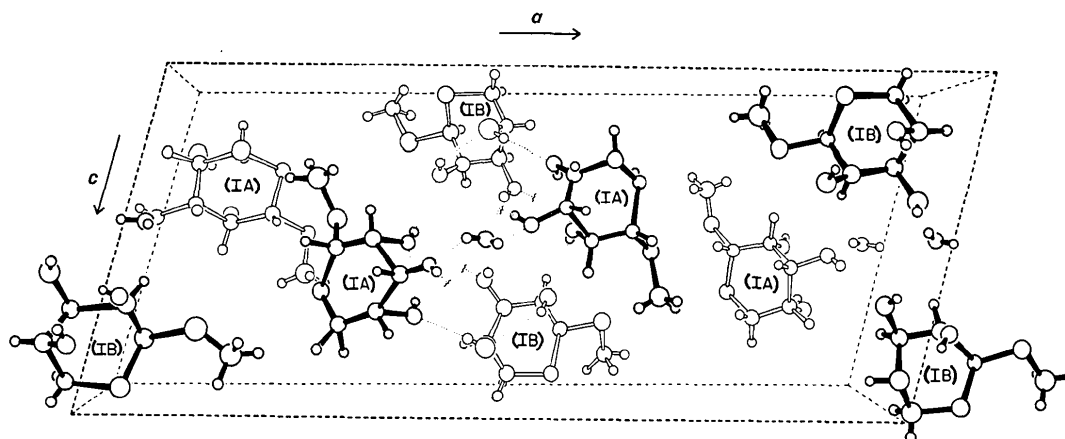


Fig. 5. Molecular arrangement in the unit cell of methyl 1,5-dithio- α -D-ribofuranose quarterhydrate.

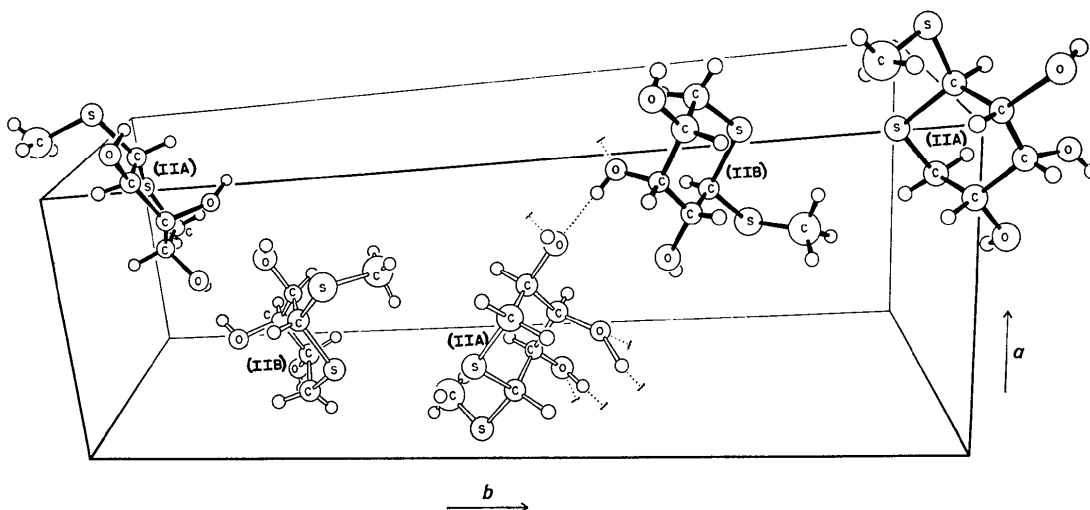


Fig. 6. Molecular arrangement in the unit cell of methyl 1,5-dithio- β -D-ribofuranoside.

of the hydrogen-atom positions, but there does appear to be a similar association of the hydroxyls to form a hydrogen-bonded column of molecules. The molecular packing is shown in Fig. 6. All $O \cdots O$ or $C \cdots O$ distances except those given in Table 4 are greater than 3.2 \AA .

In all five methyl thio-ribofuranoside crystal structures which have been studied (Girling & Jeffrey, 1973*a*, *b*), the molecular packing is such that there is a distinct segregation between the polar and non-polar groups. The infinite chains of hydrogen bonds linking the molecules three-dimensionally, which are common in carbohydrate crystal structures, do not appear in these thio derivatives. In the methyl 1-thio- α - and methyl 1,5-dithio- α - and β structures, the hydrogen bonding links the molecules so that they are packed in columns with the non-polar groups at the exterior of the columns. In the methyl 5-thio- α - and β structures, the hydrogen bonding extends across layers of molecules and the packing is characterized by alternate layers of polar and non-polar interactions. In methyl 1-thio- β -D-xylofuranoside, the molecules are cross-linked by hydrogen bonds in plates with van der Waals interactions between the plates (Mathieson & Poppleton, 1966). The distinction between these two general modes of packing appears to be related to whether the glycosidic atom is oxygen or sulfur.

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