with a carboxy O atom of an adjacent molecule and a water molecule respectively. The protonated, uncoordinated imidazole atom N(4) forms a hydrogen bond of length 2·774 (4) Å with the coordinated *W*(1). The protonated N(5) on the glycyl group participates in a hydrogen bond of length 2·997 (6) Å with *W*(3). All H atoms belonging to the water molecules are also involved in hydrogen bonding. *W*(1) and *W*(3) form hydrogen bonds with all carboxy oxygens, O(1), O(2), O(3) and O(4), with respective lengths of 2·831 (5), 2·767 (4), 2·737 (5) and 2·768 (5) Å. The water molecule *W*(2), in a special position on a diad axis, is hydrogen-bonded to *W*(3) with an associated length of 2·800 (5) Å. In this structure, therefore, all available sites participate in hydrogen bonding.

We are grateful to Mr C. W. Andrews and Professor W. E. Hatfield for providing the sample used in this study. This research was supported by US Public Health Service Grant No. ES00895-03 from the National Institute of Environmental Health Sciences.

References

Blount, J. F., Frazer, K. A., Freeman, H. C., Szymanski, J. T. & Wang, H. C. (1967). *Acta Cryst.* **22**, 396–405.

Blount, J. F., Freeman, H. C., Holland, R. V. & Milburn, G. H. W. (1970). *J. Biol. Chem.* **245**, 5177–5185.

Busing, W. R. & Levy, H. A. (1967). *Acta Cryst.* **22**, 457–464.

Camerman, N., Camerman, A. & Sarkar, B. (1976). *Canad. J. Chem.* **54**, 1309–1316.

Corfield, P. W. R., Doedens, R. J. & Ibers, J. A. (1966). *Inorg. Chem.* **6**, 197–204.

Estes, E. D. & Hodgson, D. J. (1973). *Inorg. Chem.* **12**, 2932–2935.

Freeman, H. C., Robinson, G. & Schoone, J. C. (1964). *Acta Cryst.* **17**, 719–730.

Gramaccioli, C. M. & Marsh, R. E. (1966). *Acta Cryst.* **21**, 594–600.

International Tables for X-ray Crystallography (1974). Vol. IV. Birmingham: Kynoch Press.

Meester, P. de & Hodgson, D. J. (1976). *J. Amer. Chem. Soc.* **98**, 7086–7087.

Osterberg, R. (1974). *Coord. Chem. Rev.* **12**, 309–347.

Osterberg, R., Sjoberg, B. & Soderquist, R. (1972*a*). *Acta Chem. Scand.* **26**, 4184–4185.

Osterberg, R., Sjoberg, B. & Soderquist, R. (1972*b*). *Chem. Commun.* pp. 983–985.

Pauling, L. (1960). *The Nature of the Chemical Bond*, 3rd ed. Ithaca: Cornell Univ. Press.

Stewart, R. F., Davidson, E. R. & Simpson, W. T. (1965). *J. Chem. Phys.* **42**, 3175–3187.

Acta Cryst. (1977). B**33**, 3510–3515

A Neutron Diffraction Study of the Crystal Structure of β-D-Fructopyranose*

By Shozo Takagi and G. A. Jeffrey

Chemistry Department, Brookhaven National Laboratory, Upton, New York 11973, *USA*
and The Crystallography Department, University of Pittsburgh, Pittsburgh, Pennsylvania 15260, *USA*

(*Received* 14 *March* 1977; *accepted* 9 *May* 1977)

β-D-Fructopyranose, $C_6H_{12}O_6$, crystallizes in space group $P2_12_12_1$, $Z = 4$, with $a = 9{\cdot}191$ (2), $b = 10{\cdot}046$ (2), $c = 8{\cdot}095$ (2) Å. The neutron diffraction refinement was based on an earlier X-ray study by Rosenstein (Amer. Cryst. Assoc. Meet., Abstract *KK*2, Buffalo, NY, August, 1968). The hydrogen-bonding consists of an infinite chain with a single-link side chain. Two of the hydrogen bonds involve an unusual *asymmetric bifurcated* interaction, the weak component of which is to the ring oxygen. Although this molecule is a β-ketopyranose, the C—O hemi-acetal bond lengths and valence angles are characteristic of an α-D-aldopyranose or methyl α-D-pyranoside molecule.

Introduction

This work forms part of a neutron diffraction study of simple carbohydrates, aimed at providing the accurate data relating to H atom positions which are necessary to obtain a better understanding of the rules which govern the stereochemistry of hydrogen-bonding in carbohydrate structures. Other investigations in this series are as follows: methyl α-D-altropyranoside (Poppleton, Jeffrey & Williams, 1975), methyl α-D-glucopyranoside and methyl α-D-mannopyranoside (Jeffrey, McMullan & Takagi, 1977), β-maltose monohydrate (Gress & Jeffrey, 1977), β-L-arabinose and methyl β-D-xylopyranoside (Takagi & Jeffrey, 1977), 3-amino-1,6-anhydro-3-deoxy-β-D-glucopyranose (Noordik & Jeffrey, 1977).

---

* Research supported by NIH Grant No. GM-21794, and performed under the auspices of the US Energy Research and Development Administration.

Experimental

Transparent crystals of β-D-fructose, $C_6H_{12}O_6$, suitable for neutron diffraction work, were kindly provided by Dr R. D. Rosenstein of the Department of Crystallography, University of Pittsburgh. The crystal and experimental data and structure refinement parameters are given in Table 1. The cell constants were determined by the least-squares refinement of the setting angles of 29 reflections ($45° < 2\theta < 55°$) which were centered automatically on the neutron diffractometer using the *NEXDAS* program of McMullan (1976). The wavelength of the monochromated neutron beam [Be(002) reflection with take-off angle of 34·1°] was determined by least-squares calculation from the setting angles for 29 reflections of a standard KBr crystal (a = 6·5966 Å).

The three-dimensional neutron diffraction data were collected at room temperature on a Brookhaven High Flux Beam Reactor single-crystal diffractometer operating under the control of *NEXDAS* (McMullan, 1976). The data-collection procedure is summarized in Table 1. The step-scan data were first corrected for extraneous background (*e.g.* that from the glass fiber on which the crystal was mounted) by point-by-point subtraction using an experimentally determined background curve. The background was then evaluated from counts summed at the scan extremes, using 20% of the total number of points sampled. The data were corrected for absorption using a linear absorption coefficient for neutrons, calculated from the mass absorption coefficient of 23·9 cm^2 g^{-1} for H, which corresponds to a value of 43 barns for the incoherent scattering cross-section.

Table 1. *Crystal data and neutron diffraction experimental and refinement parameters for β-D-fructose*

Crystal data

$C_6H_{12}O_6$, M_r = 180·2
a = 9·191 (2), b = 10·046 (2), c = 8·095 (2) Å
V = 747·43 Å^3
D_m = 1·597 g cm^{-3} (flotation in mixture of carbon tetrachloride and bromoform)
D_n = 1·601 g cm^{-3}
Space group $P2_12_12_1$
Z = 4

Experimental and refinement data

Crystal weight	0·00148 g
Crystal volume	0·927 mm^3
Number of faces	9
Crystal habit	{011} {111} {100} {211}
Number of reflections	
Total measured	3439 (*hkl* and $hk\bar{l}$ octants, 2θ < 90°; *hkl* and part of $hk\bar{l}$ octants, 90° < $2\theta \le$ 110°)
Averaged	1731 (69 with I < 0)
Data-collection mode, scan width	θ–2θ step scan with fixed width of 2·6° for 2θ < 60°, variable width calculated by −0·2° + 5·0° tan θ for 2θ = 60–110°
Wavelength (neutron)	1·0470 Å
Absorption correction	*ABSOR* (Templeton & Templeton, 1973)
μ (neutron)	2·569 cm^{-1}
Max. correction to F_o^2	1·307
Min. correction to F_o^2	1·172
Ave. correction to F_o^2	1·209
Number of reflections in refinement, m	1731
Number of variables, n	218
Function refined	$\Sigma w\lvert F_o^2 - K^2F_c^2\rvert^2$, where $w^{-1} = \sigma_c^2(F_o^2) + (0{\cdot}02F_o^2)^2$, and σ_c is from counting statistics

$R = \Sigma\lvert F_o^2 - K^2F_c^2\rvert/\Sigma\lvert F_o^2\rvert$ (all reflections) = 0·053
$R_w = (\Sigma w\lvert F_o^2 - K^2F_c^2\rvert^2/\Sigma w\lvert F_o^2\rvert^2)^{1/2}$ (all reflections) = 0·047
$S = [\Sigma w\lvert F_o^2 - K^2F_c^2\rvert^2/(m-n)]^{1/2} = 0{\cdot}93$
Extinction parameter, g = 0·84 (4) × 10^4

The atomic coordinates for non-hydrogen atoms from the X-ray determination (Rosenstein, 1968) were used as the initial values for refinement by full-matrix least squares using *FLINUS*, a local version of *ORFLS* (Busing, Martin & Levy, 1962). A difference Fourier map revealed the positions of all the H atoms. The function minimized was $\Sigma w\lvert F_o^2 - k^2F_c^2\rvert^2$, where w is the weight to be attached to an observation and k is a scale factor. The variable parameters for all atoms and the scale factor were refined together with the Zachariasen isotropic extinction parameter, g (Coppens & Hamilton, 1970). The extinction correction, applied to F_c^2, is given by

$$E = \left(1 + \frac{2\bar{T}F_c^2g}{V^1 \sin 2\theta}\right)^{-\frac{1}{2}}$$

where $\bar{T}$ is the effective mean path length, approximated from the calculated absorption A, by −(ln A/μ), and $V^1 = V^2/\lambda^3$. Only the reflection 120, which had an E value of 0·64, was severely affected by the extinction. The final positional parameters for all atoms are listed in Table 2. The neutron scattering lengths used were $b_C = 0{\cdot}6648$, $b_H = -0{\cdot}3740$ and $b_O = 0{\cdot}5803 \times 10^{-12}$ cm (Shull, 1972). The rigid-body motion analysis was calculated (Schomaker & Trueblood, 1968) and the results are reported in Table 3. The atomic notation and thermal ellipsoids are shown in Fig. 1 and the molecular dimensions are shown in Fig. 2.*

Discussion

The hydrogen-bonding

The structure of the hydrogen-bonding is illustrated in Fig. 3 and numerical data are given in Table 4. The

---

* Lists of observed and calculated structure factors and anisotropic thermal parameters have been deposited with the British Library Lending Division as Supplementary Publication No. SUP 32746 (13 pp.). Copies may be obtained through The Executive Secretary, International Union of Crystallography, 13 White Friars, Chester CH1 1NZ, England.

Table 2. *Fractional atomic coordinates* ($\times 10^4$) *for β-D-fructose*

Estimated standard deviations given in parentheses refer to the least significant digit.

	x	*y*	*z*
C(1)	355 (1)	1210 (1)	2787 (1)
C(2)	220 (1)	696 (1)	4553 (1)
C(3)	1197 (1)	1483 (1)	5756 (1)
C(4)	845 (1)	1137 (1)	7543 (1)
C(5)	−786 (1)	1321 (1)	7840 (1)
C(6)	−1647 (1)	515 (1)	6604 (1)
O(1)	−20 (2)	2573 (1)	2696 (2)
O(2)	625 (1)	−652 (1)	4657 (1)
O(3)	2689 (1)	1206 (1)	5456 (2)
O(4)	1627 (2)	1977 (1)	8635 (2)
O(5)	−1192 (2)	2681 (1)	7639 (2)
O(6)	−1265 (1)	871 (1)	4950 (1)
H(C11)	1471 (3)	1114 (3)	2340 (3)
H(C12)	−341 (3)	601 (3)	1996 (3)
H(C3)	979 (3)	2546 (2)	5565 (3)
H(C4)	1126 (3)	94 (2)	7783 (3)
H(C5)	−1053 (3)	982 (3)	9098 (3)
H(C61)	−1496 (3)	−555 (2)	6799 (3)
H(C62)	−2799 (2)	768 (3)	6721 (4)
H(O1)	−960 (3)	2723 (3)	3213 (4)
H(O2)	123 (3)	−1205 (2)	3840 (3)
H(O3)	3007 (3)	1677 (3)	4483 (3)
H(O4)	2359 (3)	1467 (3)	9165 (4)
H(O5)	−805 (3)	3198 (3)	8539 (3)

Table 3. *Least-squares fit to rigid-body motion for β-D-fructose*

The six atoms of the pyranose ring and the atoms C(1), O(2), O(3), O(4), O(5) are also included.

$\langle \text{r.m.s.} \lvert U_{ij} - U_{ij}\text{RBM} \rvert \rangle$	0·0011 Å^2
$\langle \text{Max.} \lvert U_{ij} - U_{ij}\text{RBM} \rvert \rangle$	0·0036
$\langle \sigma(U_{ij}) \rangle$	0·0013

Rigid-body **T** and **ω** elements and r.m.s. values for the principal axes of the **T** and **ω** tensors referred to the axes *a*, *b*, and *c*.

T	164 (5)	−8 (5)	−19 (4) (Å × 10^4)
		115 (7)	13 (5)
			160 (5)
ω	10·2 (6)	−2·6 (5)	0·8 (5) (deg^2)
		6·8 (5)	2·2 (6)
			11·7 (8)

		Direction relative to axes		
	r.m.s. values	*a*	*b*	*c*
T	0·136 Å	135·7°	77·8°	48·2°
	0·120	134·1	97·4	134·9
	0·106	93·6	165·7	76·1
ω	3·5°	96·8	66·3	24·8
	3·4	26·9	110·9	74·0
	2·1	64·2	32·5	108·4

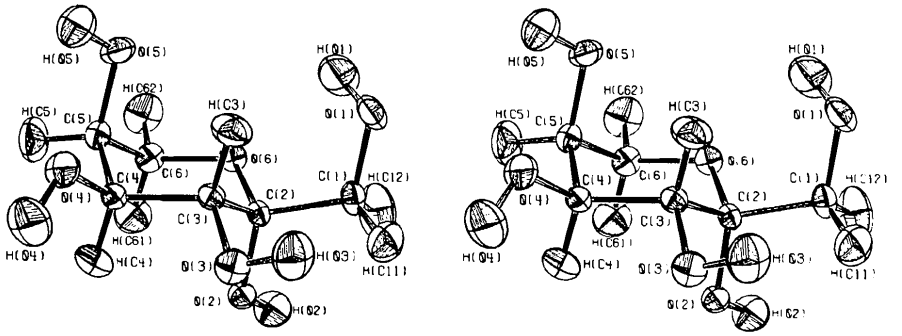

Fig. 1. Stereoview of the molecule of β-D-fructopyranose. Thermal ellipsoids are at 50% probability (Johnson, 1976).

hydrogen-bonding consists of an infinite chain which includes all the hydroxyls except O(4)H. The O(4)H hydroxyl bonds to the main chain at O(2), thereby making this O a double hydrogen-bond acceptor.

The hydroxyl O(2)H is equivalent to the anomeric hydroxyl in an aldopyranose sugar. It resembles the aldose anomeric C–OH in being adjacent to the ring O forming a hemi-acetal system C–O–C–OH, but differs in that the anomeric C–H is replaced by C–CH_2OH. It is interesting, therefore, to note that of the two characteristics that we have associated with anomeric hydroxyls (Jeffrey, Gress & Takagi, 1977; Jeffrey & Lewis, 1977), *i.e.* that they are strong hydrogen-bond donors and weak hydrogen-bond acceptors, only the first is displayed in this crystal structure. The O(2)–H···O(1) bond of 1·750 Å is the shortest in the structure. Of the other three bonds in the infinite chain, two, O(1)–H···O(3) and O(3)–H···O(5), are longer, at 1·965 and 1·977 Å, than the corresponding category of donor/acceptor bonds in the three methyl pyranosides that have been studied by neutron diffraction. In those structures, the range for this type of bond was 1·736 to 1·810 Å (Jeffrey, McMullan & Takagi, 1977). However, for both of these bonds there appear to be secondary hydrogen-bonding interactions with the ring oxygen O(6). As shown in Fig. 3, the non-linearity of the principal O–H···O interactions is such as to bring the

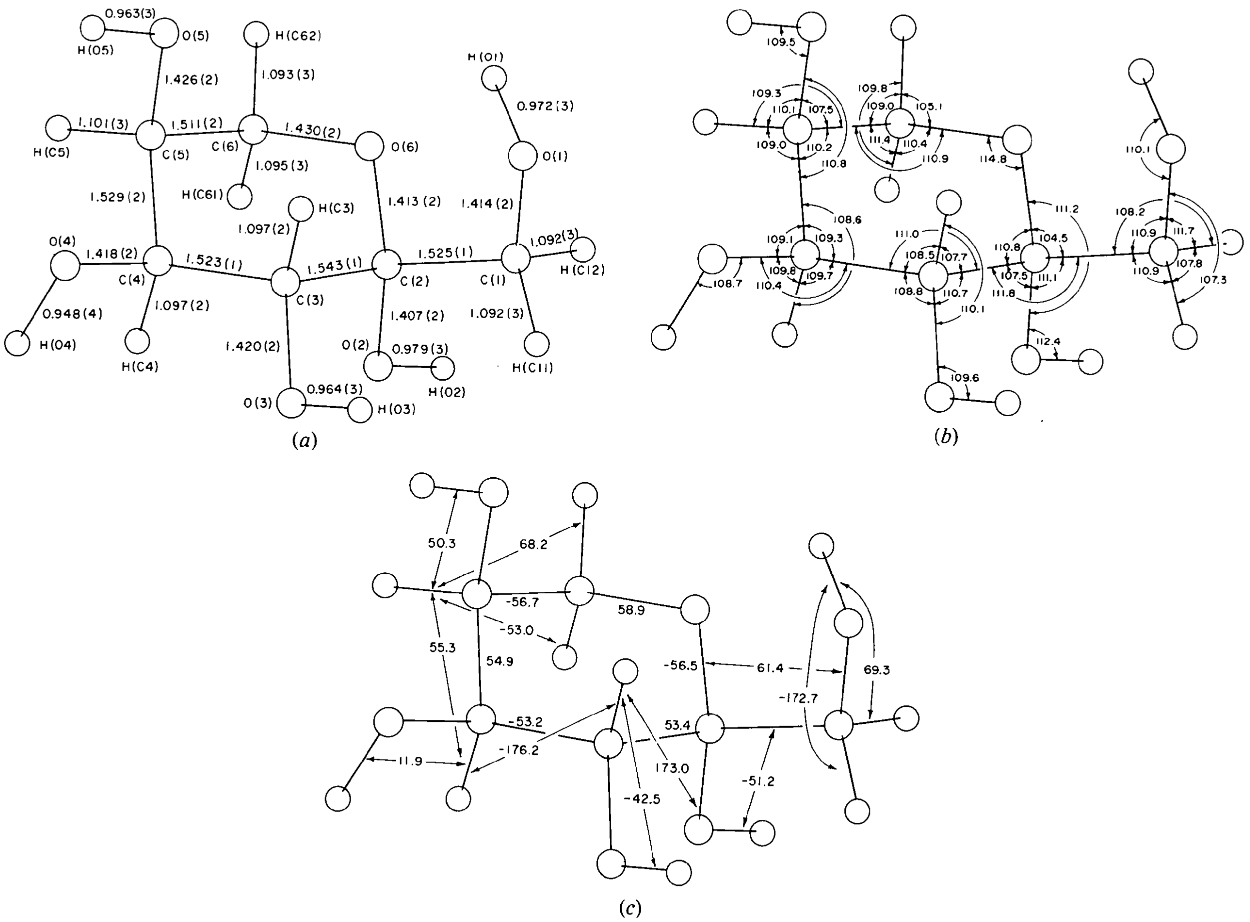

Fig. 2. Molecular dimensions of β-D-fructopyranose. (a) Bond lengths. (b) Bond angles. (c) Torsion angles.

Table 4. *Hydrogen bonds in β-D-fructose*

See also Fig. 3.

	O–H	H···O	O···O	∠O–H···O
···O–H···O–H···				
O(2)H···O(1) $[x,y,z] \rightarrow [-x, -\frac{1}{2}+y, \frac{1}{2}-z]$	0·979 (3) Å	1·750 (3) Å	2·668 (2) Å	154·6 (2)°
O(1)H···O(3) $[x,y,z] \rightarrow [-\frac{1}{2}+x, \frac{1}{2}-y, 1-z]$	0·972 (3)	1·965 (3)	2·859 (2)	152·0 (3)
O(3)H···O(5) $[x,y,z] \rightarrow [\frac{1}{2}+x, \frac{1}{2}-y, 1-z]$	0·964 (3)	1·977 (3)	2·930 (2)	169·3 (3)
O(5)H···O(2) $[x,y,z] \rightarrow [x, y, -1+z]$	0·963 (3)	1·869 (3)	2·805 (2)	163·2 (3)
O–H···O–H···				
O(4)H···O(2) $[x,y,z] \rightarrow [\frac{1}{2}-x, -y, \frac{1}{2}+z]$	0·948 (4)	2·065 (3)	2·972 (2)	159·8 (3)
··O–H··· ··· O–H ··O<				
O(1)H···O(6) (intramolecular) $[x,y,z] \rightarrow [x,y,z]$	0·972 (3)	2·349 (3)	2·750 (2)	104·0 (3)
O(3)H···O(6) $[x,y,z] \rightarrow [\frac{1}{2}+x, \frac{1}{2}-y, 1-z]$	0·964 (3)	2·593 (3)	3·107 (2)	113·6 (3)

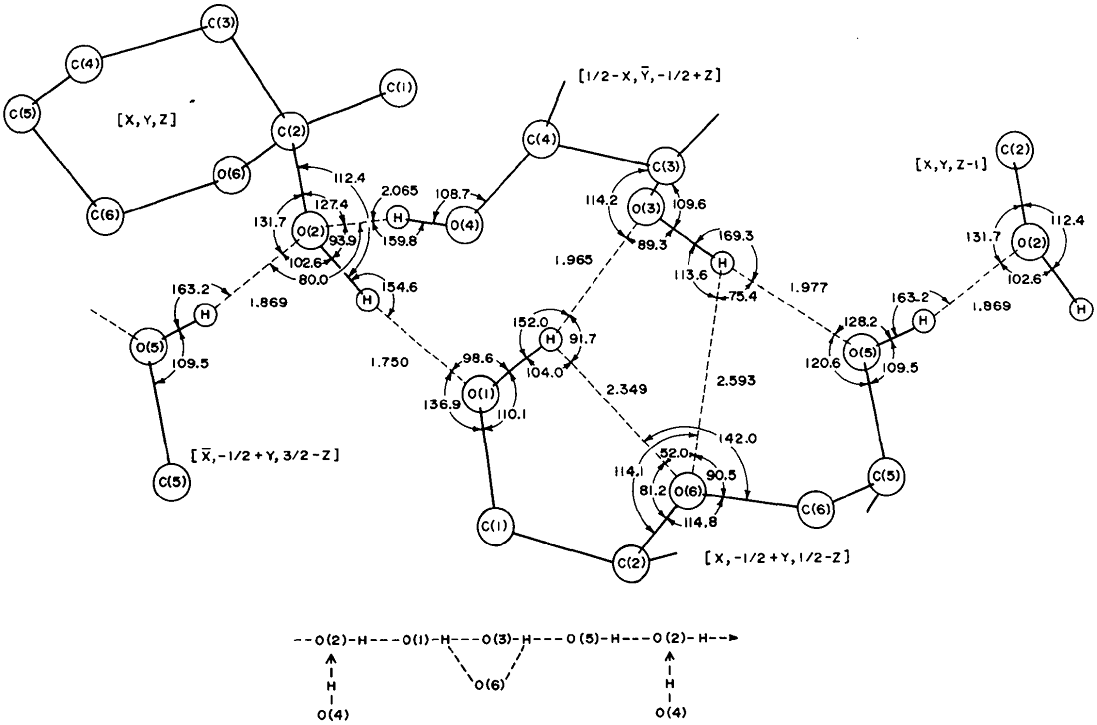

Fig. 3. Hydrogen-bonding structure in β-D-fructopyranose.

H atoms closer to O(6), suggesting that these are indeed weak bonding interactions at 2·349 and 2·593 Å. Hitherto, the bifurcated interactions which have been observed in carbohydrate crystal structures, for example, in methyl α-D-altropyranoside (Poppleton, Jeffrey & Williams, 1975), have been close to symmetrical. We propose, therefore, to distinguish between *symmetrical and asymmetrical bifurcated hydrogen bonds*, and the two examples in this structure are extreme examples of the latter class.

The molecular dimensions

The molecular dimensions of the molecule are shown in Fig. 2. The pyranose ring of the fructose molecule is close to being an ideal $^5C_2$ chair, as shown by the ring torsion angles given in Fig. 2, and by the Cremer & Pople (1975) puckering parameters, which are q_2 = 0·026 Å, q_3 = 0·555 Å, Q = 0·556 Å, φ_2 = 132·1°, θ = 2·76°. The small distortion is in the direction of a twist-boat (φ_2 = 120°). The primary alcohol group $C(1)H_2$–O(1)H is +*sc* to the ring O. In the two other ketopyranose sugars which have been studied, α-L-sorbose (Kim & Rosenstein, 1967) and α-D-tagatose (Takagi & Rosenstein, 1969), this group is disordered over the +*sc* and −*sc* orientations, which presumably have similar conformational stability.

The C–C bond lengths in this structure range from 1·511 to 1·543 Å and the C–O bond lengths from 1·414 to 1·426 Å, excluding the ring and anomeric bonds. β-D-Fructose has the same anomeric conformation as the α-D-aldoses. However, the bond lengths of 1·430, 1·413, 1·407 Å in the sequence C(6)–O(6)–C(2)–O(2) agree more closely with the mean values of these bonds in six methyl α-D-aldopyranosides [*i.e.* 1·437, 1·417, 1·407 Å; see Table 5 of Jeffrey & Takagi (1977)] than with those in seven α-aldopyranoses [*i.e.* 1·441, 1·430, 1·394 Å; see Jeffrey, Pople & Radom (1974)]. The C–H bond lengths range from 1·092 to 1·101 Å. The differences are probably not significant, owing to the uncertainty in the estimation of the thermal riding-motion effects. The O–H bond lengths range from 0·948 to 0·979 Å and again the differences are not significant.

The valence angles of particular interest are those at the ring oxygen O(6) and the anomeric carbon atom C(2). Both the C(6)–O(6)–C(2) angle of 114·8° and the O(6)–C(2)–O(2) angle of 111·2° are close to the characteristic values for α-pyranosides. In the β series, these values are close to 111 and 108° respectively (Jeffrey & Takagi, 1977).

Comparison with X-ray analysis

Following acceptance of this paper, the results of an X-ray determination were published by Kanters,

Table 5. *Hydrogen-bond distances and angles from the X-ray study by Kanters, Roelofsen, Alblas & Meinders* (1977), *when corrected to standard covalent* O–H *distances of* 0·97 Å

	H···O	O–H···O
O(2)H···O(1)	1·73 Å	161°
O(1)H···O(3)	2·03	143
O(3)H···O(5)	1·97	173
O(5)H···O(2)	1·90	155
O(4)H···O(2)	2·07	155
O(1)H···O(6)	2·40	101
O(3)H···O(6)	2·63	111

Roelofsen, Alblas & Meinders (1977). The dimensions of the molecule were the same in the two analyses for the C–C bonds and C–C–C angles within the sum of the standard deviations. The C–O distances differed by up to two standard deviations and were generally shorter in the neutron diffraction analysis. There were corresponding small differences in the C–O–C angles. The agreement in the hydrogen-bond geometry from the two structure analyses was also very good when the H positions from the X-ray study were corrected by expanding the O–H covalent bond lengths to 0·97 Å in the direction of the covalent bond, as was done in the comparison of the X-ray and neutron diffraction studies of the methyl α-D-altro-, gluco-, and manno-pyranosides by Jeffrey, McMullan & Takagi (1977).

The corrected hydrogen-bond distances and bond angles are given in Table 5, for comparison with those in Table 4. With one exception, O(4)H···O(2), the corrected X-ray H···O distances agreed with the neutron values to better than 0·01 Å. The greatest difference in the O–H···O angles was 9°. In contrast, the uncorrected X-ray H···O distances were shorter than the neutron values by up to 0·24 Å.

References

Busing, W. R., Martin, K. O. & Levy, H. A. (1962). *ORFLS*. Report ORNL-TM-305. Oak Ridge National Laboratory, Tennessee.

Coppens, P. & Hamilton, W. C. (1970). *Acta Cryst.* A**26**, 71–83.

Cremer, D. & Pople, J. A. (1975). *J. Amer. Chem. Soc.* **97**, 1354–1358.

Gress, M. E. & Jeffrey, G. A. (1977). *Acta Cryst.* B**33**, 2490–2495.

Jeffrey, G. A., Gress, M. E. & Takagi, S. (1977). *J. Amer. Chem. Soc.* **99**, 609–611.

Jeffrey, G. A. & Lewis, L. (1977). *Carbohydr. Res.* In the press.

Jeffrey, G. A., McMullan, R. K. & Takagi, S. (1977). *Acta Cryst.* B**33**, 728–737.

Jeffrey, G. A., Pople, J. A. & Radom, L. (1974). *Carbohydr. Res.* **38**, 81–95.

Jeffrey, G. A. & Takagi, S. (1977). *Acta Cryst.* B**33**, 738–742.

Johnson, C. K. (1976). *ORTEP* II. Report ORNL-5138. Oak Ridge National Laboratory, Tennessee.

Kanters, J. A., Roelofsen, G., Alblas, B. P. & Meinders, I. (1977). *Acta Cryst.* B**33**, 665–672.

Kim, S. H. & Rosenstein, R. D. (1967). *Acta Cryst.* **22**, 648–656.

McMullan, R. K. (1976). *NEXDAS, Neutron and X-ray Data Acquisition System*, Brookhaven National Laboratory.

Noordik, J. H. & Jeffrey, G. A. (1977). *Acta Cryst.* B**33**, 403–408.

Poppleton, B. J., Jeffrey, G. A. & Williams, G. J. B. (1975). *Acta Cryst.* B**31**, 2400–2404.

Rosenstein, R. D. (1968). Amer. Cryst. Assoc. Meet., Abstract *KK*2, Buffalo, New York.

Schomaker, V. & Trueblood, K. N. (1968). *Acta Cryst.* B**24**, 63–76.

Shull, C. G. (1972). Personal communication.

Takagi, S. & Jeffrey, G. A. (1977). *Acta Cryst.* B**33**, 3033–3040.

Takagi, S. & Rosenstein, R. D. (1969). *Carbohydr. Res.* **11**, 156–158.

Templeton, L. K. & Templeton, D. H. (1973). Amer. Cryst. Assoc. Meet., Abstract *E*10, Storrs, Connecticut.