

## The Crystal and Molecular Structure of $\beta$ -D-Fructose, with Emphasis on Anomeric Effect and Hydrogen-Bond Interactions

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$\beta$ -D-Fructose,  $C_6H_{12}O_6$ , is orthorhombic, space group  $P2_12_12_1$ , with  $a = 8.088(2)$ ,  $b = 9.204(4)$ ,  $c = 10.034(15)$  Å,  $Z = 4$ . The structure was solved by direct methods and refined to a final  $R$  of 0.040 for 954 counter reflexions. The molecule has the  ${}^2C_5$  pyranoside chair conformation. The C–O bond-distance variations of the hemiacetal group C–O–C–O–H are in good agreement with the variations predicted by model calculations on methoxymethanol. The molecules are held together by hydrogen bonds. The infrared spectrum shows a sharp absorption peak at a frequency near that of an unperturbed OH-group stretching vibration, indicating that one of the O–H  $\cdots$  O interactions is only weak and should probably not be considered a hydrogen bond. This is supported by model calculations on water dimers having geometries corresponding to those of the five hydrogen bonds of  $\beta$ -D-fructose.

### Introduction

$\beta$ -D-Fructose,  $C_6H_{12}O_6$ , is a naturally occurring monosaccharide. It is widely distributed as a free sugar as well as in the combined state in oligosaccharides and polysaccharides. In oligosaccharides it occurs in the furanoside form, e.g. in 1-kestose (Jeffrey & Park, 1972), melezitose monohydrate (Hirotzu & Shimada, 1973), sucrose (Brown & Levy, 1963) and raffinose pentahydrate (Berman, 1970).

Preliminary results on the structure have been reported (Rosenstein, 1968; Strahs, 1970), but no detailed description has been published.

The structures of  $\beta$ -D-fructose– $CaCl_2 \cdot 2H_2O$  (FRUC1) and bis( $\beta$ -D-fructose)– $CaCl_2 \cdot 3H_2O$  (FRUC2) (Craig, Stephenson & Stevens, 1974*a,b*) and  $\beta$ -D-fructose– $CaBr_2 \cdot 2H_2O$  (FRUC3) (Cook & Bugg, 1976) have been determined, as well as that of 1,2:4,5-di-*O*-isopropylidene- $\beta$ -D-fructopyranose (Takagi, Shiono & Rosenstein, 1973). Our interest in the geometry, molecular conformation and hydrogen-bond pattern of saccharides led us to undertake this analysis.

### Experimental

Large, colourless prismatic crystals were obtained by slow evaporation of a solution in absolute ethanol. The preliminary cell parameters and space group were determined from photographs. Accurate cell dimensions and intensities were measured on an automatic Nonius CAD-3 diffractometer with Zr-filtered Mo  $K\alpha$  radiation ( $\lambda = 0.7107$  Å). The crystal data are summarized in Table 1. Intensities were collected up to  $\sin \theta/\lambda = 0.64$  Å $^{-1}$ . From the 3273 available reflexions

Table 1. Crystal data for  $\beta$ -D-fructose

Molecular formula	$C_6H_{12}O_6$
Formula weight	180.2
Crystal system	Orthorhombic
$a$	8.088 (2) Å
$b$	9.204 (4)
$c$	10.034 (15)
Systematic absences	$h00, h = 2n + 1$ $0k0, k = 2n + 1$ $00l, l = 2n + 1$
Space group	$P2_12_12_1$
$V$	746.96 Å $^3$
$Z$	4
$D_m$	1.600 g cm $^{-3}$
$D_x$	1.601
$\mu$ (Mo $K\alpha$ )	1.56 cm $^{-1}$
Crystal dimensions	0.7 × 0.6 × 0.3 mm
$\lambda$ (Mo $K\alpha$ )	0.71069 Å

in one-half of the reflexion sphere, 136 had  $I < 2.5\sigma(I)$  and were considered unobserved. The equivalent reflexions were averaged to give 954 independent intensities and Lorentz–polarization corrections applied. No correction for absorption was made.

### Determination and refinement of the structure

The structure was solved with *MULTAN* (X-RAY system, 1972). The data were placed on an absolute scale (Wilson, 1942) and normalized structure factors calculated. 213  $|E|$  values  $> 1.20$  were used. The first  $E$  map revealed eleven of the twelve non-hydrogen atoms. Block-diagonal least-squares refinement (*CRYLSQ* of the X-RAY system, 1972) of the positions and isotropic thermal parameters of the twelve C

and O atoms followed by anisotropic thermal refinement lowered  $R$  to 0.075. A subsequent difference map revealed the 12 H atoms with electron densities ranging from 0.35 to 0.63 e  $\text{\AA}^{-3}$ . The positional parameters of the H atoms, with constant isotropic thermal parameters equal to those of the carrier atoms, were included in the refinement. The quantity minimized was  $\sum w(F_o - F_c)^2$  with weights  $w = \sigma^{-2}(F_o)$ . Standard tabulations of scattering factors were used for C and O (Cromer & Mann, 1968) and H (Stewart, Davidson & Simpson, 1965). The refinement was terminated at  $R = 0.040$  and  $R_w = 0.038$   $\{R_w = [\sum w(|F_o| - |F_c|)^2 / \sum w F_o^2]^{1/2}\}$  for 954 observed reflexions. The goodness-of-fit is 3.97, and the maximum shift/error ratio 0.066 for C and O and 0.17 for H parameters. A final difference synthesis showed no peaks above 0.25 e  $\text{\AA}^{-3}$ . Positional and thermal parameters are listed in Table 2.\*

### Description of the structure

The conformation of the molecule and the numbering of the atoms are shown in Fig. 1.

In contrast to many fructose-containing oligosaccharides where fructose occurs in several variations of furanoside twist and envelope conformations (Jeffrey, 1973a),  $\beta$ -D-fructose in the free state adopts the

six-membered  ${}^2C_5$  or  $1C(D)$  chair conformation. This also applies to the complexes FRUC1, FRUC2 (Craig, Stephenson & Stevens, 1974a,b), FRUC3 (Cook & Bugg, 1976) and to 1,2:4,5-di-*O*-isopropylidene- $\beta$ -D-fructopyranose (Takagi, Shiono & Rosenstein, 1973) in which the pyranose ring is distorted by the fused rings.

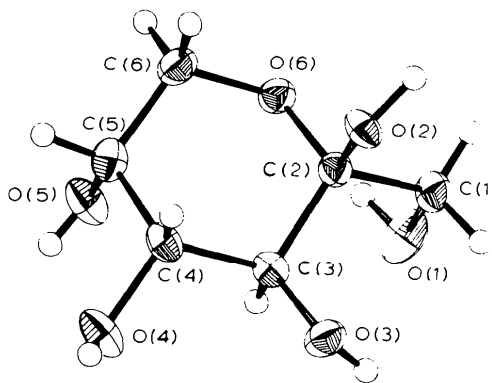


Fig. 1. Molecular conformation and atomic numbering of  $\beta$ -D-fructose. C and O atoms are represented by thermal ellipsoids at the 50% level.

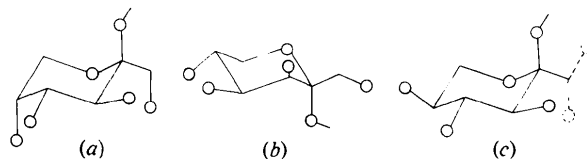


Fig. 2. Conformation of three ketohexoses: (a)  $\beta$ -D-fructose  $1C(D)$ ; (b)  $\alpha$ -D-tagatose  $1C(D)$ ; (c)  $\alpha$ -L-sorbose  $1C(L)$ .

\* A list of structure factors has been deposited with the British Library Lending Division as Supplementary Publication No. SUP 32083 (7 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 and thermal parameters for  $\beta$ -D-fructose

With the exception of isotropic thermal parameters  $B$  ( $\text{\AA}^2$ ) of hydrogen atoms, all terms are  $\times 10^4$  for C and O, and  $\times 10^3$  for H. The estimated standard deviations are given in parentheses and refer to the last decimal position of respective values. The anisotropic temperature factor is of the form  $\exp[-2\pi^2(a^*h^2U_{11} + \dots + 2b^*c^*klU_{23})]$ .

	$x$	$y$	$z$	$U_{11}$	$U_{22}$	$U_{33}$	$U_{12}$	$U_{13}$	$U_{23}$
C(1)	7215 (4)	5356 (3)	1204 (3)	213 (16)	247 (16)	336 (19)	10 (14)	-23 (14)	6 (14)
C(2)	5449 (3)	5220 (3)	703 (3)	184 (16)	214 (14)	225 (16)	14 (12)	-6 (12)	-6 (12)
C(3)	4243 (4)	6200 (3)	1480 (3)	237 (16)	226 (15)	169 (16)	20 (13)	-12 (11)	0 (12)
C(4)	2460 (4)	5846 (3)	1138 (3)	229 (17)	310 (17)	185 (15)	58 (13)	2 (13)	44 (13)
C(5)	2172 (4)	4220 (3)	1313 (3)	220 (16)	318 (18)	301 (18)	-39 (14)	-9 (14)	29 (14)
C(6)	3388 (4)	3359 (3)	518 (4)	324 (20)	232 (16)	286 (18)	-53 (13)	-22 (14)	3 (14)
O(1)	7302 (3)	4992 (2)	2580 (2)	380 (15)	341 (12)	433 (16)	-68 (11)	-210 (11)	115 (11)
O(2)	5340 (2)	5634 (2)	-649 (2)	231 (12)	340 (11)	187 (11)	53 (9)	46 (9)	0 (10)
O(3)	4538 (3)	7696 (2)	1200 (2)	283 (13)	215 (11)	372 (14)	-16 (9)	-44 (11)	-28 (9)
O(4)	1374 (3)	6627 (2)	1982 (3)	311 (14)	418 (15)	359 (15)	168 (10)	104 (12)	54 (11)
O(5)	2365 (3)	3807 (2)	2671 (2)	352 (15)	371 (14)	312 (14)	86 (12)	113 (10)	78 (10)
O(6)	5054 (2)	3736 (2)	871 (2)	214 (11)	224 (10)	305 (12)	2 (9)	-4 (9)	-26 (8)

	$x$	$y$	$z$	$B$		$x$	$y$	$z$	$B$
H(C1)	763 (3)	633 (3)	114 (3)	2.1	H'(C6)	327 (4)	239 (3)	68 (3)	2.3
H'(C1)	794 (4)	475 (3)	75 (3)	2.1	H(O1)	700 (4)	412 (4)	268 (3)	3.0
H(C3)	436 (3)	595 (3)	244 (3)	1.6	H(O2)	609 (4)	527 (3)	-112 (3)	2.0
H(C4)	222 (3)	608 (3)	28 (3)	1.9	H(O3)	529 (4)	794 (3)	153 (3)	2.4
H(C5)	102 (4)	392 (3)	107 (3)	2.3	H(O4)	90 (5)	717 (4)	160 (4)	2.7
H(C6)	325 (4)	351 (3)	-46 (3)	2.3	H(O5)	175 (4)	417 (4)	309 (3)	2.5

The pyranoside chair conformation also occurs in crystals of two other ketohexoses: in  $\alpha$ -L-sorbose (Kim & Rosenstein, 1967) the conformation is  ${}^2C_5$  or  $1C(L)$  and in  $\alpha$ -D-tagatose (Takagi & Rosenstein, 1969)  ${}^5C_2$  or  $C1(D)$  (Fig. 2).

### Bond distances

In Table 3 bond distances involving C and O atoms are compared with those of the fructose-CaCl<sub>2</sub> and fructose-CaBr<sub>2</sub> complexes. The values are in reasonable agreement with those in FRUC2 and FRUC3, whereas FRUC1 shows significant differences which, according to the authors, may be attributed to the poor quality and limited range of the diffraction data. The C—C distances of  $\beta$ -D-fructose range from 1.494 (5) to 1.540 (4) Å (mean 1.519 Å), in good agreement with the mean C—C values reported for the aldohexoses  $\beta$ -D-glucose 1.520 (Chu & Jeffrey, 1968),  $\alpha$ -D-glucose 1.523 (Brown & Levy, 1965) and  $\beta$ -D-galactose 1.524

(Longchambon, Ohannessian, Avenel & Neuman, 1975), and the ketohexoses  $\alpha$ -L-sorbose 1.516 and  $\alpha$ -D-tagatose 1.53 Å.

The endocyclic C(5)—C(6) in fructose is very short [1.494(5)], as in FRUC3 [1.487(14)] and to a lesser extent in FRUC2 [1.514(3) Å], whereas the extreme shortening in FRUC1 together with the unusual C(6)—O(6) distance possibly points to an error in the position of C(6). A similar shortening is also found in C(5)—C(6) of the aldohexoses mentioned above, where this bond is exocyclic:  $\beta$ -D-glucose 1.513,  $\alpha$ -D-glucose 1.510 and  $\beta$ -D-galactose 1.512 Å. What all the short C(5)—C(6) bonds have in common is that they involve a C atom next to the ring O atom. In  $\alpha$ -L-sorbose this shortening is absent, while the results reported in the preliminary communication on  $\alpha$ -D-tagatose do not permit a comparison.

The C—O distances range from 1.411(4) to 1.436(4) Å (mean 1.421 Å). From Table 3 it can be seen that the C—O distances compare well with those in FRUC2 and FRUC3; large discrepancies are present

Table 3. Bond distances (Å) and bond angles (°) of  $\beta$ -D-fructose involving non-hydrogen atoms with corresponding values for FRUC1, FRUC2 and FRUC3

The e.s.d.'s are given in parentheses. The e.s.d.'s for the bond angles in  $\beta$ -D-fructose are 0.2° and in FRUC3 0.5°.

	$\beta$ -D-Fructose <sup>(a)</sup>	FRUC1 <sup>(b)</sup>	FRUC2 <sup>(c)</sup>	FRUC3 <sup>(d)</sup>
C(1)—C(2)	1.520 (4)	1.505 (13)	1.521 (3)	1.530 (13)
C(2)—C(3)	1.540 (4)	1.545 (12)	1.529 (2)	1.518 (12)
C(3)—C(4)	1.518 (4)	1.518 (12)	1.520 (3)	1.527 (12)
C(4)—C(5)	1.524 (4)	1.503 (12)	1.523 (3)	1.512 (14)
C(5)—C(6)	1.494 (5)	1.432 (16)	1.514 (3)	1.487 (14)
C(1)—O(1)	1.422 (4)	1.430 (10)	1.422 (3)	1.426 (12)
C(2)—O(2)	1.411 (4)	1.404 (9)	1.406 (2)	1.414 (10)
C(3)—O(3)	1.425 (4)	1.452 (10)	1.424 (2)	1.434 (10)
C(4)—O(4)	1.415 (4)	1.420 (9)	1.424 (3)	1.436 (11)
C(5)—O(5)	1.423 (4)	1.412 (11)	1.432 (3)	1.425 (10)
C(6)—O(6)	1.436 (4)	1.525 (14)	1.437 (3)	1.456 (11)
C(2)—O(6)	1.413 (3)	1.416 (10)	1.419 (2)	1.428 (11)
O(1)—C(1)—C(2)	110.4 (2)	112.5 (7)	112.3 (2)	112.6 (5)
C(1)—C(2)—C(3)	112.3	108.2 (7)	113.7 (2)	108.6
C(1)—C(2)—O(2)	110.8	112.4 (7)	109.9 (1)	111.3
C(1)—C(2)—O(6)	104.6	108.6 (7)	103.8 (2)	106.2
C(3)—C(2)—O(2)	106.8	106.8 (6)	107.6 (1)	108.6
C(3)—C(2)—O(6)	111.2	110.0 (6)	109.7 (1)	112.6
O(2)—C(2)—O(6)	111.2	110.9 (7)	112.1 (2)	109.5
C(2)—C(3)—C(4)	111.2	113.5 (8)	110.6 (2)	115.5
C(2)—C(3)—O(3)	111.1	108.4 (6)	109.3 (2)	108.3
C(4)—C(3)—O(3)	108.8	107.7 (6)	110.8 (2)	106.8
C(3)—C(4)—C(5)	109.3	113.8 (8)	109.8 (2)	112.6
C(3)—C(4)—O(4)	110.2	110.6 (6)	110.0 (2)	109.7
C(5)—C(4)—O(4)	109.6	107.1 (6)	107.5 (2)	107.6
C(4)—C(5)—C(6)	111.1	114.6 (8)	110.1 (2)	109.5
C(4)—C(5)—O(5)	110.8	107.2 (7)	107.4 (2)	106.9
C(6)—C(5)—O(5)	107.3	113.0 (10)	114.6 (2)	112.6
C(5)—C(6)—O(6)	111.0	102.0 (9)	113.3 (2)	110.1
C(2)—O(6)—C(6)	114.6	119.5 (7)	115.0 (2)	113.8

(a) This article. (b) Craig, Stephenson & Stevens (1974a). (c) Craig, Stephenson & Stevens (1974b). (d) Cook & Bugg (1976).

in FRUC1. There is a good agreement with mean values of C—O distances in  $\alpha$ -L-sorbose (1.424), and in  $\beta$ -D-glucose (1.422),  $\alpha$ -D-glucose (1.416) and  $\beta$ -D-galactose (1.421 Å). The anomeric C(2)—O(2) distance is 1.411 (4) Å and differs by 2.5 $\sigma$  from the mean, in accordance with the anomeric shortening observed in the three fructose complexes (Table 3) as well as in  $\beta$ -D-glucose,  $\alpha$ -D-glucose and  $\beta$ -D-galactose, with anomeric bond distances of 1.383, 1.389 and 1.395 Å respectively. In a  $\alpha$ -L-sorbose the shortening is not significant.

The endocyclic C—O distances are 1.413 (3) and 1.436 (4) Å. This difference in ring C—O distances is also present in the three fructose complexes (Table 3), but the difference in C—O distances in FRUC1 (0.11 Å) is too far outside the range to be considered further. The same trend in ring C—O distances was also reported for some pyranosides (Sundaralingam, 1968; Hirotsu & Shimada, 1974). In Table 4 it is seen that the observed variations of C—O distances in the hemiacetal sequence C—O—C—O—H of fructose and its complexes, and of  $\alpha$ -L-sorbose and  $\alpha$ -D-tagatose show a shortening of the two adjacent C—O bonds (an anomeric and a ring bond respectively) and a lengthening of the other C—O bond, relative to the experimental C—O distance of 1.428 Å (Jeffrey, Pople & Radom, 1972; Kimura & Kubo, 1959) for methanol. The average C—O distance variation of the methoxymethanol moiety found in seven  $\alpha$ -pyranose structures reveals that the anomeric shortening is accompanied by a difference in the ring C—O distances such

that the C—O bond adjacent to the anomeric C—O bond is the shorter (Table 4).

The existence of a correlation between difference in ring C—O distances and anomeric shortening has been studied (Jeffrey, Pople & Radom, 1972, 1974) by model calculations on methanediol and methoxymethanol. The results of the MO calculations for both models in the stable synclinal—synclinal conformation, corresponding to that of the hemiacetal group of either

Table 5. Bond distances (Å) and bond angles ( $^{\circ}$ ) of  $\beta$ -D-fructose involving hydrogen atoms

The estimated standard deviations are given in parentheses.

C(1)—H(C1)	0.96 (3)	O(1)—H(O1)	0.84 (3)
C(1)—H'(C1)	0.93 (3)	O(2)—H(O2)	0.84 (3)
C(3)—H(C3)	1.00 (3)	O(3)—H(O3)	0.73 (3)
C(4)—H(C4)	0.91 (3)	O(4)—H(O4)	0.74 (4)
C(5)—H(C5)	1.00 (3)	O(5)—H(O5)	0.73 (3)
C(6)—H(C6)	1.00 (3)		
C(6)—H'(C6)	0.92 (3)		
H(C1)—C(1)—C(2)	112 (2)	H(C1)—C(1)—O(1)	106 (2)
H'(C1)—C(1)—C(2)	112 (2)	H'(C1)—C(1)—O(1)	108 (2)
H(C3)—C(3)—C(2)	107 (1)	H(C3)—C(3)—O(3)	114 (1)
H(C3)—C(3)—C(4)	105 (2)	H(C4)—C(4)—O(4)	108 (2)
H(C4)—C(4)—C(3)	111 (2)	H(C5)—C(5)—O(5)	105 (2)
H(C4)—C(4)—C(5)	108 (2)	H(C6)—C(6)—O(6)	108 (2)
H(C5)—C(5)—C(4)	113 (2)	H'(C6)—C(6)—O(6)	107 (2)
H(C5)—C(5)—C(6)	109 (2)	H(O1)—O(1)—C(1)	109 (2)
H(C6)—C(6)—C(5)	112 (2)	H(O2)—O(2)—C(2)	113 (2)
H'(C6)—C(6)—C(5)	111 (2)	H(O3)—O(3)—C(3)	110 (2)
H(C1)—C(1)—H'(C1)	108 (2)	H(O4)—O(4)—C(4)	111 (3)
H(C6)—C(6)—H'(C6)	108 (2)	H(O5)—O(5)—C(5)	111 (3)

Table 4. Bond-distance variations in some pyranoses, with theoretical bond-distance variations for methoxymethanol

Reference	Compound	Relative bond distances* ( $\text{\AA} \times 10^3$ )		
		C(6)—O(6)—C(2)—O(2)—H(O2)		
(a)	$\beta$ -D-Fructose	8	-15	-17
(b)	FRUC1†	97	-12	-24
(c)	FRUC2‡	9	-9	-22
(d)	FRUC3§	28	0	-14
(e)	$\alpha$ -L-Sorbose	12	-8	-13
(f)	$\alpha$ -D-Tagatose	4	-1	-22
		C(5)—O(5)—C(1)—O(1)—H(O1)		
(g)	$\alpha$ -Pyranoses, mean of 7 structures	13	2	-34
(g)	Theoretical	7	-16	-20

(a) This article. (b) Craig, Stephenson & Stevens (1974a). (c) Craig, Stephenson & Stevens (1974b). (d) Cook & Bugg (1976). (e) Kim & Rosenstein (1967). (f) Takagi & Rosenstein (1969). (g) Jeffrey, Pople & Radom (1974).

\* The numbers under the bonds are bond-distance differences; the crystallographic distances were measured relative to the experimental bond distance for methanol of 1.428 Å; the theoretical values are relative to the bond distance for methanol of 1.437 Å, calculated by *ab initio* MO methods with a Hartree-Fock/4-31 G basis set (Jeffrey, Pople & Radom, 1972; Radom, Hehre & Pople, 1972).

†  $\beta$ -D-Fructose—CaCl<sub>2</sub>·2H<sub>2</sub>O.

‡ Bis( $\beta$ -D-fructose)—CaCl<sub>2</sub>·3H<sub>2</sub>O.

§  $\beta$ -D-Fructose—CaBr<sub>2</sub>·2H<sub>2</sub>O.

C1  $\alpha$ -D-pyranoses (+*sc*, +*sc*) or 1C  $\beta$ -D-pyranoses (−*sc*, −*sc*), are in excellent agreement with the C—O distance variations observed in a number of pyranosides (Table 4). These variations can partly be explained as a local electronic effect (Romers, Altona, Buys & Havinga, 1969) caused by charge delocalization of the lone pairs of the O(H) atom on the depopulated  $2p$  orbital on the adjacent C atom, the increased back-donation in one O—C bond resulting in less back-donation in the other (Jeffrey, Pople & Radom, 1974).

The C—H distances (Table 5) are in the range 0.91 (3) to 1.00 (3) Å (mean 0.96 Å). The O—H bonds are consistently shorter (mean 0.78 Å), as is generally observed in X-ray structure investigations (Fries, Rao & Sundaralingam, 1971), as well as in neutron diffraction studies (Brown & Levy, 1965; Poppleton, Jeffrey & Williams, 1975).

### Bond angles

The C—C—C angles (Table 3) range from 109.3 (2) to 112.3 (2)° (mean 111.0°), the C—C—O angles from 104.6 (3) to 111.2 (3)° (mean 109.4°). Both means are close to tetrahedral, as in the three fructose complexes (Table 3). A significant deviation from the mean is found in the exocyclic C—C—O angle involving O(6); these angles are 104.6 (2) in  $\beta$ -D-fructose, 103.8 (2) in FRUC2 and 106.2 (5)° in FRUC3. In  $\alpha$ -D-tagatose and  $\alpha$ -L-sorbose the angles are 106 and 106.9 (3)° respectively. A similar deviation is found in the corresponding exocyclic angle C(6)—C(5)—O(5) in  $\alpha$ -D-glucose [108.1 (2)],  $\beta$ -D-glucose [107.1 (3)],  $\alpha$ -L-fucose [105.2 (5)] and  $\beta$ -D-galactose [106.5 (1)°]. The angle of 114.6 (2)°, subtended at O(6), is consistent with values reported for other carbohydrates (Sundaralingam, 1968).

The mean of angles involving aliphatic H atoms (Table 5) is 109°, that of angles involving hydroxyl H atoms 111°. This indicates that, despite shortening of O—H and C—H distances, the direction of these bonds

is close to tetrahedral, as is often observed in H-atom positions resulting from neutron and X-ray diffraction analyses.

### Molecular conformation

The conformational ring angles of  $\beta$ -D-fructose (Table 6) range from 52.2 to 58.0°, which is close to the range 55.8–61.7° reported for an ideal, strain-free pyranose ring (Kim & Jeffrey, 1967) and is well within the range 50–65° observed for some ten pyranose structures (Jeffrey, 1973*a*). The deviations from the three least-squares planes, each comprising two op-

Table 7. *Least-squares planes of  $\beta$ -D-fructose and its salt complexes, with displacements of the atoms from the plane*

Asterisks indicate atoms which were not included in the calculation of the plane.

	Displacements from the plane (Å)			
	$\beta$ -D-Fructose <sup>(a)</sup>	FRUC1 <sup>(b)</sup>	FRUC2 <sup>(c)</sup>	FRUC3 <sup>(d)</sup>
C(2)	0.014	0.080	−0.020	0.076
C(3)	−0.014	−0.080	0.019	−0.073
C(5)	0.014	0.087	−0.019	0.074
C(6)	−0.014	−0.086	0.020	−0.077
C(4)*	−0.659	−0.527	−0.669	−0.545
O(6)*	0.600	0.604	0.588	0.614
C(3)	−0.005	−0.072	0.018	−0.067
C(4)	0.004	0.070	−0.018	0.067
C(6)	−0.005	−0.070	0.019	−0.071
O(6)	0.005	0.071	−0.019	0.071
C(2)*	−0.620	−0.526	−0.656	−0.515
C(5)*	0.661	0.632	0.640	0.658
C(4)	0.003	−0.003	−0.004	0.002
C(5)	−0.003	0.003	0.004	−0.002
O(6)	0.004	−0.004	−0.004	0.002
C(2)	−0.003	0.003	0.004	−0.002
C(3)*	−0.644	−0.477	−0.684	−0.475
C(6)*	0.644	0.735	0.596	0.696

(a) This article. (b) Craig, Stephenson & Stevens (1974*a*). (c) Craig, Stephenson & Stevens (1974*b*). (d) Cook & Bugg (1976).

Table 6. *Endocyclic torsion angles (°) of  $\beta$ -D-fructose and FRUC1, FRUC2 and FRUC3*

The torsion angle  $A(1)–A(2)–A(3)–A(4)$  is viewed along  $A(2)–A(3)$ , with a clockwise rotation of  $A(1)$  to  $A(4)$  taken to be positive.

	$\beta$ -D-Fructose <sup>(a)</sup>	FRUC1 <sup>(b)</sup>	FRUC2 <sup>(c)</sup>	FRUC3 <sup>(d)</sup>
O(6)—C(2)—C(3)—C(4)	−52.7	−37.2	−57.2	−39.0
C(2)—C(3)—C(4)—C(5)	+52.2	+38.0	+56.6	+39.4
C(3)—C(4)—C(5)—C(6)	−54.7	−53.9	−52.8	−49.8
C(4)—C(5)—C(6)—O(6)	+56.5	+60.1	+51.3	+61.3
C(5)—C(6)—O(6)—C(2)	−58.0	−64.3	−54.7	−63.6
C(3)—C(2)—O(6)—C(6)	+55.6	+53.4	+56.3	+50.9

(a) This article. (b) Craig, Stephenson & Stevens (1974*a*). (c) Craig, Stephenson & Stevens (1974*b*). (d) Cook & Bugg (1976).

posite ring bonds, show a slight distortion related to the plane of the C(2)–C(3) and C(5)–C(6) bonds (Table 7). In FRUC2 the range of the ring torsion angles ( $51.3$ – $57.2^\circ$ ) indicates absence of distortion; the ranges in FRUC1 and FRUC3,  $56.6$ – $74.5$  and  $39.0$ – $63.6^\circ$  respectively, being outside the normal range, reveal an appreciable strain, as do the deviations from the least-squares planes (Table 7). The exocyclic torsion angles (Table 8) are close to the ideal values of  $60$  and  $180^\circ$  respectively; small deviations are found in the angles around C(2)–C(3).

The primary O–H group of  $\beta$ -D-fructose is *gauche* relative to O(6) and C(3), so the conformation around C(1)–C(2) is *gauche-gauche*, implying a *trans* conformation of O(1) relative to axially oriented O(2). In FRUC3 and FRUC1 the primary O–H group is *gauche-trans*, whereas in FRUC2 the conformation is the same as in  $\beta$ -D-fructose. In  $\alpha$ -D-tagatose (Fig. 2), with a  ${}^5C_2$  chair, the conformation around C(1)–C(2) is *gauche-trans*, with O(1) *gauche* with respect to axial O(2). Here the *gauche-gauche* conformation is unfavourable because of the *peri* interaction of *syn*-axial O(1) and O(3) (Jeffrey, 1973*b*). The primary O–H group of  $\alpha$ -L-sorbose (Fig. 2) is found to be in two orientations (Kim & Rosenstein, 1967): 63% *gauche-trans* and 37% *gauche-gauche*. The third non-eclipsing conformation, *trans-gauche*, is apparently unfavourable, as follows from its rare occurrence in pyranose structures (Longchambon, Ohannessian, Avenel & Neuman, 1975; Kanters, Roelofsen, Doesburg & Koops, 1976).

### Hydrogen bonding

In Table 9 intermolecular distances  $< 3.20 \text{ \AA}$  are listed together with distance and angle parameters describing hydrogen bonds. The hydrogen bonds are intermolecular and all hydroxyl groups act as hydrogen donors; O(2) is twice an acceptor, O(1), O(3) and O(5) once, whereas hydroxyl group O(4) and ring O(6) do not accept a hydrogen bond. The interactions involving O(3)–H(O3) are of bifurcated type, though the O(3)–H(O3)  $\cdots$  O(6') geometry with O(3)  $\cdots$  O(6')  $3.11$ ,

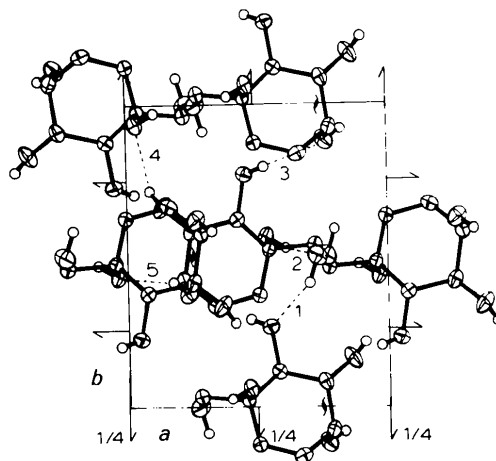


Fig. 3. A view of the structure of  $\beta$ -D-fructose down *c*. Hydrogen bonds, numbered according to Table 9, are indicated by dashed lines.

Table 8. *Exocyclic torsion angles* ( $^\circ$ ) *of*  $\beta$ -D-fructose

O(1)–C(1)–C(2)–C(3)	58.4	O(3)–C(3)–C(4)–C(5)	174.9
O(1)–C(1)–C(2)–O(2)	177.7	O(3)–C(3)–C(4)–O(4)	–64.7
O(1)–C(1)–C(2)–O(6)	–62.4	C(3)–C(4)–C(5)–O(5)	64.5
C(1)–C(2)–C(3)–C(4)	–169.6	O(4)–C(4)–C(5)–C(6)	–175.5
C(1)–C(2)–C(3)–O(3)	69.1	O(4)–C(4)–C(5)–O(5)	–56.3
O(2)–C(2)–C(3)–C(4)	68.8	O(5)–C(5)–C(6)–O(6)	–64.8
O(2)–C(2)–C(3)–O(3)	–52.5	C(1)–C(2)–O(6)–C(6)	177.1
O(6)–C(2)–C(3)–O(3)	–174.0	O(2)–C(2)–O(6)–C(6)	–63.3
C(2)–C(3)–C(4)–O(4)	172.7		

Table 9. *Intermolecular* O  $\cdots$  O *distances*  $< 3.20 \text{ \AA}$ , *and corresponding hydrogen-bond geometry* in  $\beta$ -D-fructose

	Hydrogen bond	O–H ( $\text{\AA}$ )	H $\cdots$ O ( $\text{\AA}$ )	O $\cdots$ O ( $\text{\AA}$ )	Angle ( $^\circ$ )		Symmetry operation*
					O–H $\cdots$ O	O $\cdots$ O	
1	O(1)–H(O1) $\cdots$ O(3')	0.84	2.13	2.859	145.0	645.4	645.4
2	O(2)–H(O2) $\cdots$ O(1')	0.84	1.86	2.670	161.4	664.2	664.2
3	O(3)–H(O3) $\cdots$ O(5')	0.73	2.21	2.934	171.5	655.4	655.4
4	O(4)–H(O4) $\cdots$ O(2')	0.74	2.28	2.974	156.7	465.3	465.3
5	O(5)–H(O5) $\cdots$ O(2')	0.73	2.12	2.809	157.7	565.2	565.2
6	O(3)–H(O3) $\cdots$ O(6')	0.73	2.72	3.109	115.9	655.4	655.4

\* The symmetry operation is performed on atom O'. The first set of numbers specifies the lattice translations, e.g. 645.4 is  $+a-b$  from 555.4. The last digit indicates one of the following symmetry operations: (1)  $x, y, z$ . (2)  $\frac{1}{2} - x, -y, \frac{1}{2} + z$ . (3)  $\frac{1}{2} + x, \frac{1}{2} - y, -z$ . (4)  $-x, \frac{1}{2} + y, \frac{1}{2} - z$ .

H(O3)···O(6') 2.72 Å and O(3)–H(O3)···O(6') 115.9° is well outside the range usually considered normal for a hydrogen bond. Similar weak bifurcated interactions occur in sucrose (Brown & Levy, 1963, 1973) and methyl  $\alpha$ -D-glucopyranoside (Berman & Kim, 1968). The hydrogen bonds are shown in Fig. 3, which represents a projection of the crystal structure down **a**.

The geometric criterion for hydrogen bonds states that an O–H···O contact, with O···O and H···O distances less than 3.00 and 2.40 Å respectively, should be considered a hydrogen bond. As was shown recently, a large deviation from linearity is allowed (Kroon, Kanters, van Duijneveldt–van de Rijdt, van Duijneveldt & Vliegthart, 1975). Kanters, Kroon, Peerdeman & Vliegthart (1969) noted that inspection of the region of the infrared O–H stretching vibration can be helpful in depicting O–H···O interactions as hydrogen bonds. From this study, which comprised a large number of crystals of organic compounds containing aliphatic O–H groups, it emerged that in some cases the infrared spectra show a distinct, sharp absorption at about 3500 cm<sup>-1</sup>, which is close to the value of about 3580 cm<sup>-1</sup> reported for the stretching vibration of a free, unperturbed O–H group (Coggeshall & Saier, 1951; Joesten & Schaad, 1974; Wilmshurst, 1956). In crystals, hydrogen bonding between aliphatic O–H groups gives rise to a broad absorption band near 3400 cm<sup>-1</sup>. Because of the observed distinct stretching vibration the corresponding O–H···O interactions can best be looked upon as very weak hydrogen bonds, if hydrogen bonds at all.

As can be seen from Fig. 4, the infrared spectrum of  $\beta$ -D-fructose contains a sharp absorption peak at 3525 cm<sup>-1</sup>, well separated from the broad absorption band centred at about 3400 cm<sup>-1</sup>. As it is generally accepted (Lindgren & Tegenfeldt, 1974) that infrared frequencies and intensities associated with motions of the O–H···O system constitute molecular properties that change in a characteristic way when a molecule becomes engaged in a hydrogen bond, the spectrum permits the conclusion that in crystalline  $\beta$ -D-fructose at least one of the O–H groups interacts only very weakly. Though in  $\beta$ -D-fructose two O···O contacts, O(3)···O(5') 2.934 and O(4)···O(2') 2.974 Å (Table 9), lie close to the limiting value of 3.00 Å, it is risky to relate these contacts to the observed sharp absorption peak, because no simple relation seems to exist between  $\nu_{OH}$  and donor–acceptor distance (Ratajczak & Orville-Thomas, 1967; Lindgren & Tegenfeldt, 1974). A better starting-point is the linear relationship between shift of  $\nu_{OH}$  and lengthening of donor O–H distance resulting from model calculations on hydrogen-bonded water molecules (Lindgren & Tegenfeldt, 1974), though this relationship cannot be put to a test because of a lack of desired accuracy of experimental O–H lengths. From recent *ab initio* SCF calculations on the water

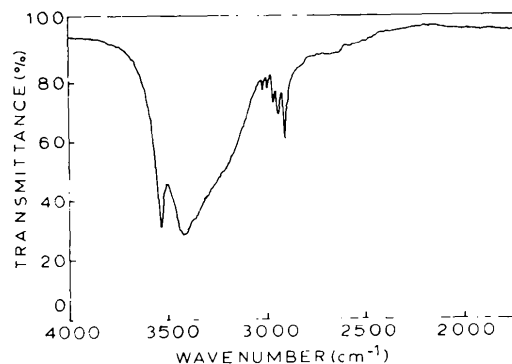


Fig. 4. Infrared spectrum of the region 2000–4000 cm<sup>-1</sup> of  $\beta$ -D-fructose in a KBr pellet.

dimer (Kroon, Kanters, van Duijneveldt–van de Rijdt, van Duijneveldt & Vliegthart, 1975) it appears that, in addition to the usual O···O distance, angular parameters describing the relative orientation of donor and acceptor water molecules are important in determining the hydrogen-bond energy. This outcome led us to calculate the donor O–H lengths in water dimer configurations representing the five hydrogen-bond interactions observed in  $\beta$ -D-fructose. For this purpose each hydrogen-bond interaction is replaced by one between a donor and an acceptor water molecule, and in these fixed orientations the energy was minimized with respect to the donor O–H length. Preliminary results (van Duijneveldt–van de Rijdt, van Duijneveldt & Kanters, 1977) indicate that the relation between donor O–H length (and hence  $\nu_{OH}$ ) and the various orientational parameters is a complex one, but so far they support previous conclusions that the O···O distance is not decisive in determining the hydrogen-bond interaction energy nor the donor O–H length. In particular, it appears that the arrangement O(1)–H(O1)···O(3') with O···O 2.859 Å and O–H···O 145° (Table 9) is the one which gives rise to a negligible shift of  $\nu_{OH}$  and thus could account for the observed sharp absorption peak in Fig. 4; moreover its energy turns out to be only about one-half that of normal hydrogen bonds.

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