

tierungen herstellen kann, ergeben sich entscheidende Vorteile, da dann der volle Öffnungswinkel des Monochromators genutzt wird. Für die Praxis wird dieses Verfahren nur in speziellen Fällen anwendbar sein.

Zylindrisch gebogene Monochromatorkristalle stellen dagegen praktisch keine Forderung an die Form des Kristalls, die nicht erfüllbar wäre. Kristalle von z.B. $0,1 \times 0,05 \times 0,05$ mm haben bereits eine ausreichende Grösse, um quantitative Messung in noch erträglichen Messzeiten durchzuführen, wenn $\mu \cdot 0,005$ (cm) (μ = Absorptionskoeffizient) nicht klein gegen 1 ist. Die homogene Intensität muss nur senkrecht zur Drehachse gewährleistet sein, um eine sichere quantitative Messung zu ermöglichen, das ist aber nach den obigen Ausführungen durch den Verzicht auf die Fokussierung des Öffnungswinkels ϵ_x^0 leicht zu erfüllen.

Die Untersuchung von sehr kleinen Kristallen mit normalen Monochromatoren scheidet meist daran, dass man nicht verhindern kann, dass mehr Streumasse des Präparatträgers als vom zu untersuchenden Kristall durch den Primärstrahl getroffen wird. Bei fokussierenden Monochromatoren in der Anordnung gemäss Fig. 2 kann jedoch der Röntgenstrahl allein auf den Kristall konzentriert werden, da die Öffnungsbegrenzung von ϵ_x^0 sehr 'scharf' eingehalten werden kann. Bei extrem kleinen Kristallen empfiehlt es sich zur Vermeidung von Luftstreuung, den Strahlengang des Pri-

märstrahle ins Vakuum zu legen oder die gesamte Kamera zu evakuieren.

Die monochromatische Methode hat auch für grössere Kristalle kaum Nachteile gegenüber dem sonst üblichen polychromatischen Verfahren; sie gestattet wegen des grossen Abstands Röhre-Kristall bequeme Handhabung und liefert auch für Kristalle normaler Grösse den üblichen Methoden überlegene Resultate. Es ist bedauerlich, dass die gegenwärtige Diffraktometertechnik von diesen Vorzügen keinen Gebrauch macht; denn alle auf dem Markt befindlichen Geräte sind für das hier beschriebene Verfahren ungeeignet.

Diese Untersuchung wurde im Rahmen des Schwerpunktprogramms 'Strukturforschung' der Deutschen Forschungsgemeinschaft durchgeführt. Ihr gebührt aufrichtiger Dank für die Bereitstellung von Monochromatoren und Kameras.

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The Crystal Structure of L-Ascorbic Acid, 'Vitamin C'. I. The X-ray Analysis

BY JAN HVOSLEF

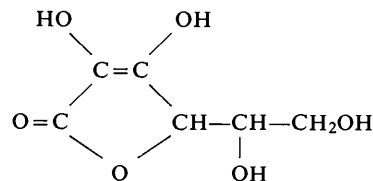
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(Received 7 January 1967)

The crystal and molecular structure of L-ascorbic acid has been determined and the parameters refined to a final *R* index of 5.0% by means of 1640 X-ray reflexions. The space group is $P2_1$ with the axes $a = 17.299$, $b = 6.353$, $c = 6.411$ Å and $\beta = 102^\circ 11'$. The four molecules in the unit cell are related in pairs by pseudo screw axes, and each molecule consists of an almost planar five-membered ring plus a side chain. The atomic distances are in general accordance with the accepted values for different hybridizations. The enediol group is planar, and one of the hydrogen atoms attached to an oxygen atom in this group is picked out as the probably protolytic one. All hydrogen bonds are intermolecular and consist partly of helices running along [001] and partly of isolated bonds. Evidence is found of systematic shortening of the C–H and O–H bonds when determined by X-ray diffraction compared with those found by neutron diffraction.

Introduction

Herbert, Hirst, Percival, Reynolds & Smith (1933) determined the chemical constitution of the substance isolated by Szent-Györgyi (1928) called hexuronic acid. Later the name was changed to ascorbic acid, as the substance was proved to be identical with the active factor in Holst & Frölich's (1907) cure of animals suffering from scurvy. In a series of chemical experiments they proved the substance to have the following structural formula:



which implies a carbon-carbon double bond in a five-membered ring. The acidic character of this compound ($pK_1 = 4.26$, $pK_2 = 11.64$) was explained by the enediol grouping. In an early X-ray investigation Cox (1932)

found that an almost planar molecule would account satisfactorily for the crystallographic properties. This view was later supported by Cox & Goodwin (1936) in an attempt to give a model of the crystal structure. However, only 15 intensities were used, and this is far too small a number to give any conclusive choice between different alternatives. The proposed structure is in error, but their conclusion that the two molecules in the asymmetric unit are connected by a pseudo symmetry element is in principle correct.

There are many reasons for a renewed inspection of this structure. The particular interest in L-ascorbic acid lies in its biological importance and also in its acidity and reducing power. It was hoped that it would be possible to decide which of the two hydrogen atoms in the enediol grouping protolyse most easily. A crystallographic investigation of the sodium salt is in progress in order to see what actually happens to the molecule under salt formation. Other items of interest are the various C-C and C-O bonds of different hybridizations, and the hydrogen bond system. A neutron diffraction analysis of two projections has been undertaken in order to determine the hydrogen positions with some precision, and to compare these with the results of the X-ray analysis. An account of the neutron diffraction analysis will be given in a separate paper.

Experimental

The nature and habit of single crystals of L-ascorbic acid have been discussed by Cox & Goodwin (1936), by Hendricks (1934) and by Niggli (1942). The present investigation includes axial determinations by rotation and Weissenberg diagrams and by Guinier photographs calibrated against potassium chloride. A survey of the different results is given in Table 1.

Many crystals were examined in order to find one which gave satisfactory quality of the X-ray diagrams. It was observed that different crystals gave quite different secondary extinction effects, and the crystal finally chosen for collection of three-dimensional X-ray data was cut from a large single crystal. This crystal did not have the perfect appearance of the very small specimens, but gave satisfactory optical extinctions. The shape was approximately cubic with edge lengths equal to 0.24 mm. The linear absorption coefficient μ was 13.9 cm^{-1} . No correction for absorption was performed because of the negligible variation of the transmission over the angular range.

X-ray intensities were collected on an integrating Weissenberg camera, using Ni-filtered Cu $K\alpha$ radiation

($\lambda = 1.5418$). The six layers recorded by rotation about **b** and the five layers recorded by rotation about **c** were measured photometrically. Copper radiation allows a maximum of 1640 unique reflexions for this unit cell, and 1572 were actually strong enough to be measured. The zero observed reflexions were included according to Hamilton (1955) by taking one-third of the minimum observable intensity, except for the $h0l$ zone, where one-quarter of the minimum was used.

The various levels were placed on an approximately absolute scale by means of the calculated structure factors of the solved structure in the $h0l$ zone. In this zone $F_{(\text{absol.})}$, B , and unitary structure factors U were determined statistically.

Unit cell and space group

$$V = 688.59 \text{ \AA}^3$$

$$d_{\text{calc}} = 1.699 \text{ g.cm}^{-3}$$

$$M = 176.13$$

$$Z = 4$$

Space group $P2_1$.

With four molecules in the unit cell there are two in the asymmetric unit, but as stated earlier they are related by a pseudo symmetry operation. This has been discussed by Cox & Goodwin (1936) and later by Bunn (1945), although their conclusions are incomplete. In the present text the two molecules have been labelled *A* and *B*, and the atoms in molecule *B* are marked with asterisks so that the generally accepted indexing can be maintained.

In the $hk0$ zone all intensities for h odd are very weak or absent, and in the $h0l$ zone the following intensities are systematically small: for $l = 4n$ and $h = 2n + 1$, and for $l = 2n + 2$ and $h = 2n$. The pseudo symmetry element arising from this rule is a twofold screw axis along $[010]$ in the position ($x = \frac{1}{4}; z = \frac{3}{8}$) and in ($x = \frac{3}{4}; z = \frac{5}{8}$). An alternative way of describing this operation is a transfer of molecule *A* into the position of molecule *B'* by adding $\frac{1}{2}$ to the x , zero to the y and $-\frac{1}{4}$ to the z parameters where *B'* is the symmetry equivalent of *B* by the true screw axis. The average values for the refined structure for the five-membered ring are: $x = 0.5038$, $y = 0.0006$, $z = -0.2425$.

The discrepancies are much larger for the atoms in the side chains.

Solution of the structure

It was a complicating feature that the orientations of the side chains in the molecules were unknown, and

Table 1. Axial lengths (\AA) and angles

	<i>a</i>	<i>b</i>	<i>c</i>	β
Cox & Goodwin	16.95 \AA	6.32 \AA	6.38 \AA	102° 30'
Niggli	17.12	6.29	6.40	102 10
Weissenberg (Hvoslef, 1964)	17.20	6.37	6.40	102 05
Guinier method (this investigation)	17.299 (8)	6.353 (3)	6.411 (3)	102 11 (08')

it soon became obvious that it was a hopeless task to solve the structure by Patterson studies. The sharpening of this function did, however, give a rough idea of the orientation of the five-membered ring, and it also became possible to discard the model proposed by Cox & Goodwin.

The hope was now to try direct methods, and to use the data in the centrosymmetric **b** projection. This seemed quite favorable since the *b* axis is only 6.411 Å, but it turned out that the values of the unitary structure factors *U* were low. The highest value was 0.40, and no signs were found by inequality relations. The next step was to try the Sayre equation for the largest *U* values. According to Grison's (1951) criteria for the use of Sayre equations, no conclusions could be drawn in the present case. Nevertheless, 13 relations of the type $s(\mathbf{h})s(\mathbf{h}')s(\mathbf{h}+\mathbf{h}') = +1$ were picked out as reasonably probable. Two structure factors were given the sign symbols *a* and *b*. By using the procedure described by Zachariasen (1952) and by Woolfson (1961), 41 signs were expressed by the two sign symbols. The four corresponding Fourier maps were calculated in the hope that at least the five-membered rings could be identified. The maps were difficult to interpret, and several trials were made without success. It was generally possible to reach an *R* index of 40%, but the interatomic distances gradually became unacceptable during the refinements.

It was thus necessary to extend the number of sign symbols in the original set of Sayre equations. The set is given in Table 2 and the statistically determined *U* values and their signs are given in Table 3. Further progress was again made by using the equation $s(\mathbf{h}) = s[\sum_{\mathbf{h}'} s(\mathbf{h}')s(\mathbf{h}+\mathbf{h}')]$, and finally 52 signs were expressed in terms of *a*, *b* and *c*.

Table 2. The 13 basic Sayre relations

$s(302)s(803)s(11,0,5) = +1$
$s(302)s(404)s(106) = +1$
$s(302)s(404)s(706) = +1$
$s(302)s(905)s(607) = +1$
$s(302)s(105)s(207) = +1$
$s(302)s(305)s(607) = +1$
$s(102)s(706)s(608) = +1$
$s(701)s(404)s(11,0,5) = +1$
$s(203)s(404)s(207) = +1$
$s(502)s(404)s(106) = +1$
$s(502)s(11,0,5)s(607) = +1$
$s(502)s(106)s(608) = +1$
$s(14\ 0\ 1)s(706)s(707) = +1$

Table 3. The basic unitary structure factors and their sign symbols

The asterisks indicate the original choice of symbols.

<i>h</i>	<i>k</i>	<i>l</i>	<i>U</i>	Sign symbol
7	0	1	0.26	<i>a</i>
14	0	1	0.36	<i>abc</i>
1	0	2	0.28	<i>b</i>
*3	0	2	0.37	+
-5	0	2	0.25	<i>ab</i>

Table 3 (cont.)

<i>h</i>	<i>k</i>	<i>l</i>	<i>U</i>	Sign symbol
8	0	3	0.25	+?
-2	0	3	0.28	<i>bc</i>
*4	0	4	0.37	<i>b</i>
*-4	0	4	0.34	<i>a</i>
3	0	5	0.30	<i>ab</i>
*11	0	5	0.36	+
*-1	0	5	0.30	<i>c</i>
-9	0	5	0.33	<i>abc</i>
7	0	6	0.34	<i>b</i>
-1	0	6	0.40	<i>a</i>
-7	0	6	0.32	+?
2	0	7	0.30	<i>c</i>
6	0	7	0.22	<i>ab</i>
7	0	7	0.27	<i>abc</i>
-6	0	7	0.27	<i>abc</i>
-6	0	8	0.29	<i>b</i>

Since no convincing relations between these symbols were found, the Fourier maps for all eight possible sign combinations were calculated. The correct set turned out to be the one where $a = -$, $b = +$, $c = +$, and the trial structure based upon these signs gradually refined to an *R* index of 20%. It turned out that six of the original signs were wrong, leading to an incorrect position of one oxygen atom. This was taken care of by means of an 'error' synthesis, and a subsequent least-squares refinement gave an *R* index of 9.4% for the *h0l* data.

The approximate *y* coordinates were stipulated by means of the *hk0* Patterson projection, which clearly showed that the five-membered rings were almost normal to the *b* axis. This projection suffers from heavy overlap, and no attempt was made to bring the *R* index below 20%. As the space group is non-centrosymmetric it was decided to keep the *y* parameter for O(1) fixed.

Refinement of the structure

The three-dimensional refinement was performed by using a full-matrix least-squares program which was originally written by Gantzel, Sparks & Trueblood (I. U. Cr. *World List of Crystallographic Computer Programs*, no. 384). This program has since been revised and adapted for UNIVAC 1107 by C. Rømming at this institute. Since the number of atomic parameters exceeded the machine capacity, the refinement had to be split into parts. The function to be minimized was

$$\sum_{hkl} w_{hkl}^2 (|F_{\text{obs}}| - G|F_{\text{calc}}|)^2$$

where w_{hkl} is the weight function and *G* is the reciprocal scale factor. The following weight scheme was found satisfactory: for F_{obs} less than 4.0 $w_{hkl} = 8$, and for larger values $w_{hkl} = 16 (F_{\text{obs}})^{-\frac{1}{2}}$.

Starting with the parameters giving $R = 9.4\%$ in the **b** projection and 20% in the **c** projection, the first cycle of three-dimensional least-squares refinement varying all atoms isotropically gave an *R* index of 17.2%. Only the F_{obs} larger than 10.0 were used. This limit was gradually reduced, and the interlayer scaling

was checked from time to time. After a few cycles the R index was 10.4%, and at this point the hydrogen atoms were included. Their positions were roughly known from difference maps and the preliminary neutron analysis. Both positional and isotropic thermal parameters were refined, and this reduced the R index to 9%. It is, however, to be noted that for the least-squares refinement a collection of 1498 reflexions was used so that some large F_{obs} of low order were absent. Some of these have quite a strong contribution from the hydrogen atoms, especially $F(302)$.

It was at this stage necessary to correct for secondary extinction effects in the crystal, and the formula given by Zachariasen (1963)

$$F_{\text{corr}} = K \cdot F_{\text{obs}}(1 + \beta_{2\theta} C \cdot I_{\text{obs}})$$

was employed. A program written for UNIVAC 1107 by E. Christensen at this institute determined the value of C to be 1.31×10^{-5} .

When the hydrogen positions no longer shifted, the analysis of the C and O atoms was extended to include anisotropic thermal vibrations. After a number of cycles, ensuring that all reflexions had been included in the least-squares procedure, the R index was 5.0% for all 1640 structure factors.

During the refinement it became clear that a significant difference existed between the positions of the hydrogen atoms as determined by neutrons and by X-rays. To test this, the neutron parameters for hydrogen were introduced into the refinement of the X-ray parameters, in order to see whether these would give a better fit. The result was, however, that the hydrogen atoms converged into the positions originally found by X-rays. The change in R index by this shift was small, but the change in F_{calc} was quite significant for a number of low order structure factors.

The final atomic parameters and their standard deviations are given in Table 4, while Table 5 includes the observed and extinction corrected structure factors.

Table 4. Fractional coordinates x , y and z of atoms in the asymmetric unit of the L-ascorbic acid unit cell

Each coordinate is followed by its least-squares standard deviation in parentheses. The hydrogen atoms are identified by the C or O atoms to which they are attached.

	x	y	z
O(1)	-0.0145 (1)	0.9434 (6)	1.0204 (3)
O(2)	-0.0694 (1)	0.9326 (6)	0.5453 (3)
O(3)	0.0884 (1)	0.9366 (6)	0.3919 (3)
O(4)	0.1080 (1)	0.9590 (6)	0.9548 (3)
O(5)	0.1669 (1)	0.5811 (5)	0.8281 (4)
O(6)	0.3173 (1)	0.9824 (6)	0.9004 (4)
O(1)*	0.5109 (1)	0.4344 (6)	0.2228 (3)
O(2)*	0.5649 (1)	0.4338 (6)	0.6997 (3)
O(3)*	0.4077 (1)	0.4513 (7)	0.8500 (3)
O(4)*	0.3886 (1)	0.4403 (6)	0.2867 (3)
O(5)*	0.3269 (1)	0.0841 (5)	0.4966 (4)
O(6)*	0.1855 (1)	0.4807 (5)	0.2561 (4)
C(1)	0.0284 (2)	0.9495 (7)	0.8923 (4)
C(2)	0.0062 (2)	0.9429 (7)	0.6602 (4)
C(3)	0.0731 (2)	0.9436 (7)	0.5860 (4)
C(4)	0.1425 (2)	0.9558 (8)	0.7689 (5)

Table 4 (cont.)

	x	y	z
C(5)	0.2009 (2)	0.7747 (6)	0.7822 (5)
C(6)	0.2743 (2)	0.8061 (7)	0.9574 (6)
C(1)*	0.4686 (2)	0.4405 (7)	0.3515 (5)
C(2)*	0.4896 (2)	0.4449 (7)	0.5825 (5)
C(3)*	0.4228 (2)	0.4514 (7)	0.6556 (5)
C(4)*	0.3535 (2)	0.4607 (7)	0.4717 (5)
C(5)*	0.2919 (2)	0.2896 (7)	0.4705 (5)
C(6)*	0.2285 (2)	0.2875 (7)	0.2662 (6)
O(2) H	-0.104 (2)	0.968 (6)	0.623 (5)
O(3) H	0.048 (2)	0.930 (9)	0.296 (6)
O(5) H	0.131 (3)	0.561 (9)	0.724 (8)
O(6) H	0.362 (2)	0.987 (8)	0.974 (6)
O(2)*H	0.601 (2)	0.484 (7)	0.637 (5)
O(3)*H	0.456 (3)	0.436 (13)	0.945 (8)
O(5)*H	0.339 (2)	0.079 (9)	0.614 (8)
O(6)*H	0.174 (2)	0.529 (8)	0.143 (7)
C(4) H	0.176 (1)	1.101 (5)	0.764 (4)
C(5) H	0.216 (2)	0.769 (6)	0.649 (4)
C(6) H(1)	0.262 (2)	0.833 (6)	1.101 (5)
H(2)	0.317 (2)	0.692 (6)	0.975 (5)
C(4)*H	0.326 (2)	0.606 (6)	0.458 (5)
C(5)*H	0.267 (1)	0.324 (5)	0.595 (4)
C(6)*H(1)	0.252 (1)	0.260 (5)	0.141 (4)
H(2)	0.186 (1)	0.169 (6)	0.268 (5)

Fig. 1 shows the composite drawing of a three-dimensional Fourier map and a survey of the structure. The positive direction of \mathbf{b} is *into* the paper, and this choice of axes conforms with the absolute configuration of L-ascorbic acid. This has been established mainly on the basis of degradation of the tetramethyl derivative to 3,4 dimethyl-L-threonamide, whose configuration is established by conversion to (+)-tartaric acid.

Results and discussion of the structure

Distances and angles in the two independently determined molecules are given in Table 6. In the same Table the average values are given, and these are included in Fig. 2. The standard deviation σ for each value is given in parentheses, and it is noted that except for the external angles about C(1) the discrepancies are within 3σ . The value of σ in the averaged model is assumed to be $(1/\sqrt{2})\sigma$.

Molecular geometry

The two molecules have different environments and hence different packing conditions. This has consequences for the side chains where the conformation about the C(4)-C(5) bond is slightly different in the two cases, and also for the planarity of the five-membered rings.

Although the system defined by the

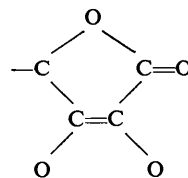


Table 5. Observed and calculated structure factors

F_obs are corrected for secondary extinction effects, and the zero observed reflexions are included by taking one-third of the minimum observable intensities, except for the h0l zone, where one-quarter was taken.

Table with 24 columns: h, k, l, F_obs, F_calc, h, k, l, F_obs, F_calc, h, k, l, F_obs, F_calc, h, k, l, F_obs, F_calc, h, k, l, F_obs, F_calc. The table contains a grid of numerical data representing structure factors for various hkl reflections.

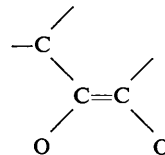
Table 5 (cont.)

h k l F _{obs} F _{calc}				h k l F _{obs} F _{calc}				h k l F _{obs} F _{calc}				h k l F _{obs} F _{calc}			
8 4 3	4.4	2.6	-5	7 1	7.6	4.1	11 4 2	12.7	11.8	13 0 3	9.7	9.6	15 0 0	2.9	3.1
8 4 4	4.4	4.7	-5	7 1	10.7	11.0	11 4 2	12.7	11.8	13 0 3	9.7	9.6	15 0 0	2.9	3.1
8 4 5	4.4	5.5	-5	7 1	12.2	13.0	11 4 3	13.2	12.5	13 0 3	9.7	9.6	15 0 0	2.9	3.1
8 4 6	4.4	6.0	-5	7 1	12.8	13.7	11 4 4	13.7	13.0	13 0 3	9.7	9.6	15 0 0	2.9	3.1
8 4 7	4.4	6.6	-5	7 1	13.4	14.4	11 4 5	14.2	13.5	13 0 3	9.7	9.6	15 0 0	2.9	3.1
8 4 8	4.4	7.2	-5	7 1	14.0	15.1	11 4 6	14.7	14.0	13 0 3	9.7	9.6	15 0 0	2.9	3.1
8 4 9	4.4	7.9	-5	7 1	14.6	15.8	11 4 7	15.2	14.5	13 0 3	9.7	9.6	15 0 0	2.9	3.1
8 4 10	4.4	8.6	-5	7 1	15.2	16.5	11 4 8	15.7	15.0	13 0 3	9.7	9.6	15 0 0	2.9	3.1
8 4 11	4.4	9.3	-5	7 1	15.8	17.2	11 4 9	16.2	15.5	13 0 3	9.7	9.6	15 0 0	2.9	3.1
8 4 12	4.4	10.0	-5	7 1	16.4	17.9	11 4 10	16.7	16.0	13 0 3	9.7	9.6	15 0 0	2.9	3.1
8 4 13	4.4	10.7	-5	7 1	17.0	18.6	11 4 11	17.2	16.5	13 0 3	9.7	9.6	15 0 0	2.9	3.1
8 4 14	4.4	11.4	-5	7 1	17.6	19.3	11 4 12	17.7	17.0	13 0 3	9.7	9.6	15 0 0	2.9	3.1
8 4 15	4.4	12.1	-5	7 1	18.2	20.0	11 4 13	18.2	17.5	13 0 3	9.7	9.6	15 0 0	2.9	3.1
8 4 16	4.4	12.8	-5	7 1	18.8	20.7	11 4 14	18.7	18.0	13 0 3	9.7	9.6	15 0 0	2.9	3.1
8 4 17	4.4	13.5	-5	7 1	19.4	21.4	11 4 15	19.2	18.5	13 0 3	9.7	9.6	15 0 0	2.9	3.1
8 4 18	4.4	14.2	-5	7 1	20.0	22.1	11 4 16	19.7	19.0	13 0 3	9.7	9.6	15 0 0	2.9	3.1
8 4 19	4.4	14.9	-5	7 1	20.6	22.8	11 4 17	20.2	19.5	13 0 3	9.7	9.6	15 0 0	2.9	3.1
8 4 20	4.4	15.6	-5	7 1	21.2	23.5	11 4 18	20.7	20.0	13 0 3	9.7	9.6	15 0 0	2.9	3.1
8 4 21	4.4	16.3	-5	7 1	21.8	24.2	11 4 19	21.2	20.5	13 0 3	9.7	9.6	15 0 0	2.9	3.1
8 4 22	4.4	17.0	-5	7 1	22.4	24.9	11 4 20	21.7	21.0	13 0 3	9.7	9.6	15 0 0	2.9	3.1
8 4 23	4.4	17.7	-5	7 1	23.0	25.6	11 4 21	22.2	21.5	13 0 3	9.7	9.6	15 0 0	2.9	3.1
8 4 24	4.4	18.4	-5	7 1	23.6	26.3	11 4 22	22.7	22.0	13 0 3	9.7	9.6	15 0 0	2.9	3.1
8 4 25	4.4	19.1	-5	7 1	24.2	27.0	11 4 23	23.2	22.5	13 0 3	9.7	9.6	15 0 0	2.9	3.1
8 4 26	4.4	19.8	-5	7 1	24.8	27.7	11 4 24	23.7	23.0	13 0 3	9.7	9.6	15 0 0	2.9	3.1
8 4 27	4.4	20.5	-5	7 1	25.4	28.4	11 4 25	24.2	23.5	13 0 3	9.7	9.6	15 0 0	2.9	3.1
8 4 28	4.4	21.2	-5	7 1	26.0	29.1	11 4 26	24.7	24.0	13 0 3	9.7	9.6	15 0 0	2.9	3.1
8 4 29	4.4	21.9	-5	7 1	26.6	29.8	11 4 27	25.2	24.5	13 0 3	9.7	9.6	15 0 0	2.9	3.1
8 4 30	4.4	22.6	-5	7 1	27.2	30.5	11 4 28	25.7	25.0	13 0 3	9.7	9.6	15 0 0	2.9	3.1
8 4 31	4.4	23.3	-5	7 1	27.8	31.2	11 4 29	26.2	25.5	13 0 3	9.7	9.6	15 0 0	2.9	3.1
8 4 32	4.4	24.0	-5	7 1	28.4	31.9	11 4 30	26.7	26.0	13 0 3	9.7	9.6	15 0 0	2.9	3.1
8 4 33	4.4	24.7	-5	7 1	29.0	32.6	11 4 31	27.2	26.5	13 0 3	9.7	9.6	15 0 0	2.9	3.1
8 4 34	4.4	25.4	-5	7 1	29.6	33.3	11 4 32	27.7	27.0	13 0 3	9.7	9.6	15 0 0	2.9	3.1
8 4 35	4.4	26.1	-5	7 1	30.2	34.0	11 4 33	28.2	27.5	13 0 3	9.7	9.6	15 0 0	2.9	3.1
8 4 36	4.4	26.8	-5	7 1	30.8	34.7	11 4 34	28.7	28.0	13 0 3	9.7	9.6	15 0 0	2.9	3.1
8 4 37	4.4	27.5	-5	7 1	31.4	35.4	11 4 35	29.2	28.5	13 0 3	9.7	9.6	15 0 0	2.9	3.1
8 4 38	4.4	28.2	-5	7 1	32.0	36.1	11 4 36	29.7	29.0	13 0 3	9.7	9.6	15 0 0	2.9	3.1
8 4 39	4.4	28.9	-5	7 1	32.6	36.8	11 4 37	30.2	29.5	13 0 3	9.7	9.6	15 0 0	2.9	3.1
8 4 40	4.4	29.6	-5	7 1	33.2	37.5	11 4 38	30.7	30.0	13 0 3	9.7	9.6	15 0 0	2.9	3.1
8 4 41	4.4	30.3	-5	7 1	33.8	38.2	11 4 39	31.2	30.5	13 0 3	9.7	9.6	15 0 0	2.9	3.1
8 4 42	4.4	31.0	-5	7 1	34.4	38.9	11 4 40	31.7	31.0	13 0 3	9.7	9.6	15 0 0	2.9	3.1
8 4 43	4.4	31.7	-5	7 1	35.0	39.6	11 4 41	32.2	31.5	13 0 3	9.7	9.6	15 0 0	2.9	3.1
8 4 44	4.4	32.4	-5	7 1	35.6	40.3	11 4 42	32.7	32.0	13 0 3	9.7	9.6	15 0 0	2.9	3.1
8 4 45	4.4	33.1	-5	7 1	36.2	41.0	11 4 43	33.2	32.5	13 0 3	9.7	9.6	15 0 0	2.9	3.1
8 4 46	4.4	33.8	-5	7 1	36.8	41.7	11 4 44	33.7	33.0	13 0 3	9.7	9.6	15 0 0	2.9	3.1
8 4 47	4.4	34.5	-5	7 1	37.4	42.4	11 4 45	34.2	33.5	13 0 3	9.7	9.6	15 0 0	2.9	3.1
8 4 48	4.4	35.2	-5	7 1	38.0	43.1	11 4 46	34.7	34.0	13 0 3	9.7	9.6	15 0 0	2.9	3.1
8 4 49	4.4	35.9	-5	7 1	38.6	43.8	11 4 47	35.2	34.5	13 0 3	9.7	9.6	15 0 0	2.9	3.1
8 4 50	4.4	36.6	-5	7 1	39.2	44.5	11 4 48	35.7	35.0	13 0 3	9.7	9.6	15 0 0	2.9	3.1
8 4 51	4.4	37.3	-5	7 1	39.8	45.2	11 4 49	36.2	35.5	13 0 3	9.7	9.6	15 0 0	2.9	3.1
8 4 52	4.4	38.0	-5	7 1	40.4	45.9	11 4 50	36.7	36.0	13 0 3	9.7	9.6	15 0 0	2.9	3.1
8 4 53	4.4	38.7	-5	7 1	41.0	46.6	11 4 51	37.2	36.5	13 0 3	9.7	9.6	15 0 0	2.9	3.1
8 4 54	4.4	39.4	-5	7 1	41.6	47.3	11 4 52	37.7	37.0	13 0 3	9.7	9.6	15 0 0	2.9	3.1
8 4 55	4.4	40.1	-5	7 1	42.2	48.0	11 4 53	38.2	37.5	13 0 3	9.7	9.6	15 0 0	2.9	3.1
8 4 56	4.4	40.8	-5	7 1	42.8	48.7	11 4 54	38.7	38.0	13 0 3	9.7	9.6	15 0 0	2.9	3.1
8 4 57	4.4	41.5	-5	7 1	43.4	49.4	11 4 55	39.2	38.5	13 0 3	9.7	9.6	15 0 0	2.9	3.1
8 4 58	4.4	42.2	-5	7 1	44.0	50.1	11 4 56	39.7	39.0	13 0 3	9.7	9.6	15 0 0	2.9	3.1
8 4 59	4.4	42.9	-5	7 1	44.6	50.8	11 4 57	40.2	39.5	13 0 3	9.7	9.6	15 0 0	2.9	3.1
8 4 60	4.4	43.6	-5	7 1	45.2	51.5	11 4 58	40.7	40.0	13 0 3	9.7	9.6	15 0 0	2.9	3.1
8 4 61	4.4	44.3	-5	7 1	45.8	52.2	11 4 59	41.2	40.5	13 0 3	9.7	9.6	15 0 0	2.9	3.1
8 4 62	4.4	45.0	-5	7 1	46.4	52.9	11 4 60	41.7	41.0	13 0 3	9.7	9.6	15 0 0	2.9	3.1
8 4 63	4.4	45.7	-5	7 1	47.0	53.6	11 4 61	42.2	41.5	13 0 3	9.7	9.6	15 0 0	2.9	3.1
8 4 64	4.4	46.4	-5	7 1	47.6	54.3	11 4 62	42.7	42.0	13 0 3	9.7	9.6	15 0 0	2.9	3.1
8 4 65	4.4	47.1	-5	7 1	48.2	55.0	11 4 63	43.2	42.5	13 0 3	9.7	9.6	15 0 0	2.9	3.1
8 4 66	4.4	47.8	-5	7 1	48.8	55.7	11 4 64	43.7	43.0	13 0 3	9.7	9.6	15 0 0	2.9	3.1
8 4 67	4.4	48.5	-5	7 1	49.4	56.4	11 4 65	44.2	43.5	13 0 3	9.7	9.6	15 0 0	2.9	3.1
8 4 68	4.4	49.2	-5	7 1	50.0	57.1	11 4 66	44.7	44.0	13 0 3	9.7	9.6	15 0 0	2.9	3.1
8 4 69	4.4	49.9	-5	7 1	50.6	57.8	11 4 67	45.2	44.5	13 0 3	9.7	9.6	15 0 0	2.9	3.1
8 4 70	4.4	50.6	-5	7 1	51.2	58.5	11 4 68	45.7	45.0	13 0 3	9.7	9.6	15 0 0	2.9	3.1
8 4 71	4.4	51.3	-5	7 1	51.8	59.2	11 4 69	46.2	45.5	13 0 3	9.7	9.6	15 0 0	2.9	3.1
8 4 72	4.4	52.0	-5	7 1	52.4	59.9	11 4 70	46.7	46.0	13 0 3	9.7	9.6	15 0 0	2.9	3.1
8 4 73	4.4	52.7	-5	7 1	53.0	60.6	11 4 71	47.2	46.5	13 0 3	9.7	9.6	15 0 0	2.9	3.1
8 4 74	4.4	53.4	-5	7 1	53.6	61.3	11 4 72	47.7	47.0	13 0 3	9.7	9.6	15 0 0	2.9	3.1
8 4 75	4.4	54.1	-5	7 1	54.2	62.0	11 4 73	48.2	47.5	13 0 3	9.7	9.6	15 0 0	2.9	3.1
8 4 76	4.4	54.8	-5	7 1	54.8	62.7	11 4 74	48.7	48.0	13 0 3	9.7	9.6	15 0 0	2.9	3.1
8 4 77	4.4	55.5	-5	7 1	55.4	63.4	11 4 75	49.2	48.5	13 0 3	9.7	9.6	15 0 0	2.9	3.1
8 4 78	4.4	56.2	-5	7 1	56.0	64.1	11 4 76	49.7	49.0	13 0 3	9.7	9.6	15 0 0	2.9	3.1
8 4 79	4.4	56.9	-5	7 1	56.6	64.8	11 4 77	50.2	49.5	13 0 3	9.7	9.6	15 0 0	2.9	3.1
8 4 80	4.4	57.6	-5	7 1	57.2	65.5	11 4 78	50.7	50.0	13 0 3	9.7	9.6	15 0 0	2.9	3.1
8 4 81	4.4	58.3	-5	7 1	57.8	66.2	11 4 79	51.2	50.5	13 0 3	9.7	9.6	15 0 0	2.9	3.1
8 4 82	4.4	59.0	-5	7 1	58.4	66.9	11 4 80	51.7	51.0	13 0 3	9.7	9.6	15 0 0	2.9	3.1
8 4 83	4.4	59.7	-5	7 1	59.0	67.6	11 4 81	52.2	51.5	13 0 3	9.7	9.6	15 0 0	2.9	3.1
8 4 84	4.4	60.4	-5	7 1	59.6	68.3									

Table 6. Distances (Å) and angles (°) in the two independently determined molecules of L-ascorbic acid

Distance	Standard deviations are given in parentheses		
	Molecule A	Molecule B	Average
C(1)=O(1)	1.218 (3)	1.213 (3)	1.216 (2)
C(2)—O(2)	1.361 (3)	1.362 (3)	1.361 (2)
C(3)—O(3)	1.327 (4)	1.326 (4)	1.326 (3)
C(1)—O(4)	1.352 (3)	1.358 (3)	1.355 (2)
C(4)—O(4)	1.441 (4)	1.448 (4)	1.444 (2)
C(5)—O(5)	1.421 (5)	1.434 (5)	1.427 (3)
C(6)—O(6)	1.434 (5)	1.429 (5)	1.431 (4)
C(2)=C(3)	1.341 (3)	1.335 (4)	1.338 (2)
C(1)—C(2)	1.457 (4)	1.448 (4)	1.452 (3)
C(3)—C(4)	1.493 (4)	1.494 (4)	1.493 (3)
C(4)—C(5)	1.521 (5)	1.521 (5)	1.521 (4)
C(5)—C(6)	1.521 (4)	1.521 (5)	1.521 (3)
Angle			
C(4)—O(4)—O(5)	109.2 (2)	109.0 (2)	109.1 (2)
O(4)—C(1)—C(2)	109.6 (2)	109.4 (2)	109.5 (2)
C(1)—C(2)—C(3)	107.5 (2)	108.1 (2)	107.8 (2)
C(2)—C(3)—C(4)	109.4 (2)	109.5 (2)	109.5 (2)
C(3)—C(4)—O(4)	104.2 (2)	103.7 (2)	104.0 (2)
O(4)—C(1)—O(1)	121.9 (3)	120.9 (3)	121.4 (3)
O(1)—C(1)—C(2)	128.4 (2)	129.7 (2)	129.1 (2)
C(1)—C(2)—O(2)	124.7 (2)	124.5 (2)	124.6 (2)
O(2)—C(2)—C(3)	127.7 (3)	127.3 (3)	127.5 (2)
C(2)—C(3)—O(3)	133.7 (3)	133.3 (3)	133.5 (2)
O(3)—C(3)—C(4)	116.9 (2)	117.2 (2)	117.1 (2)
C(3)—C(4)—C(5)	114.8 (3)	114.8 (3)	114.8 (2)
O(4)—C(4)—C(5)	110.5 (3)	110.3 (3)	110.4 (2)
C(4)—C(5)—O(5)	111.6 (2)	111.8 (2)	111.7 (2)
C(4)—C(5)—C(6)	112.5 (3)	112.8 (3)	112.7 (2)
O(5)—C(5)—C(6)	106.1 (3)	107.6 (3)	106.9 (2)
C(5)—C(6)—O(6)	108.1 (3)	107.8 (3)	108.0 (2)

group may be regarded as roughly planar, it has not been possible to find a plane where all the atoms are situated within three times the standard deviation from this plane. It may therefore be stated that the ring is significantly non-planar. Common to both molecules is, however, an almost exact planarity of the



group which involves the *enediol* part of the molecule.

Investigations of *lactone* groups —C—C—O—C— in six-



membered rings by Mathieson & Taylor (1961) and Mathieson (1963) and in five membered rings by Kim, Jeffrey, Rosenstein & Corfield (1967) and Jeffrey, Rosenstein & Vlasse (1967) show that these are generally planar. In comparison with other molecules involved in these investigations, additional strain is present in L-ascorbic acid on account of the double bond in the ring. Attempts to calculate the best planes through the lactone groups revealed that these are significantly non-planar and different in the two molecules. This difference is best described in terms of

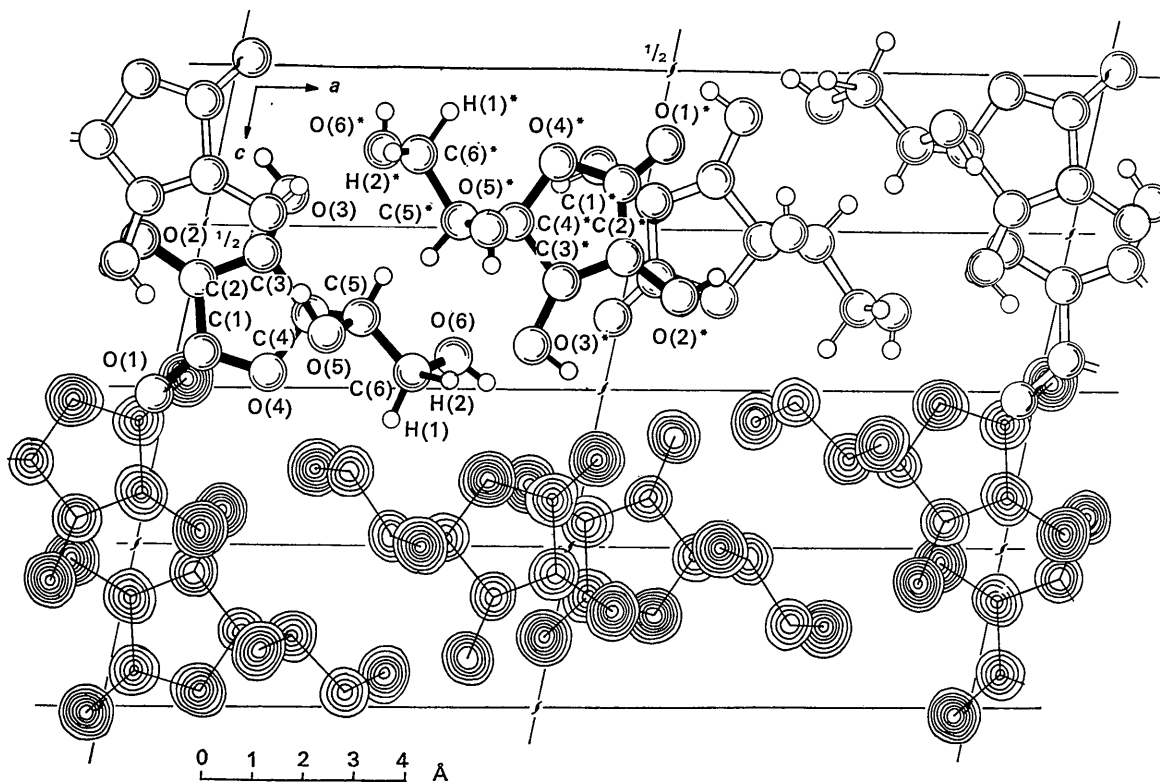
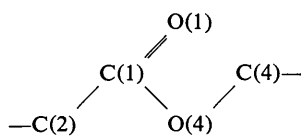
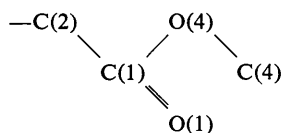


Fig. 1. View of the structure of L-ascorbic acid along [010] and the corresponding composite three-dimensional electron density. Contours at intervals of $2 \text{ e.}\text{\AA}^{-3}$, starting at $3 \text{ e.}\text{\AA}^{-3}$. The reference molecules are indicated by solid lines. Small circles represent hydrogen atoms.

alternative zigzag chains. In molecule *A* the chain is indicated by



whereas in *B* it is



The reason for this difference is probably the close approach of the O(5) atom to the O(4) atom in molecule *A*. This unbonded distance is 2.798 Å, while in molecule *B* the value is 2.950 Å even with O(4) protruding over the best plane on the same side as the O(5) atom. It is not unlikely that the hydrogen bond forces are the origin of the difference in the conformation about C(4)–C(5) in the two molecules. Hence it is probably justifiable to conclude that such bonds may perturb lactone groups in strained five membered rings.

The best planes through the lactone and the enediol groups in each molecule are at only 0.6° to each other at the most, and their averaged normals form angles of 3° to the [010] direction. Table 7 gives the atomic distances from the planes and their standard deviations.

Inspection of the carbon atoms in the side chains revealed some minor deviations from the ideal 'staggered' arrangement. The geometry of the two –CH(OH)CH₂OH groups is almost exactly the same, and in both molecules C(6)–O(6) are rotated by 8.3° about the C(5)–C(6) bond relative to the ideal 'staggered' arrangement. The entire side chains are rotated by 7.9° about C(4)–C(5), but in opposite directions in *A* and in *B* relative to the same ideal arrangement. This is easily seen when viewed in the [010] direction, but hardly visible in the [001] direction. As a consequence

Table 7. Distances from the best planes through parts of the ring system in L-ascorbic acid

Standard deviations are given in the parentheses

	Molecule <i>A</i>	Molecule <i>B</i>	
O(2)	0.0008 (37)	–0.0034 (40)	enediol group
O(3)	–0.0002 (41)	0.0002 (40)	
C(2)	–0.0014 (45)	0.0047 (46)	
C(3)	0.0004 (46)	0.0008 (48)	
C(4)	0.0004 (49)	–0.0024 (47)	
C(2)	0.0025 (45)	–0.0139 (46)	lactone group
C(1)	0.0110 (46)	0.0008 (45)	
O(1)	–0.0127 (39)	0.0192 (40)	
O(4)	0.0113 (35)	–0.0346 (38)	
C(4)	–0.0122 (49)	0.0285 (47)	

of this, the pseudo symmetry is more nearly perfect in the *hk0* zone than in the *h0l* zone.

Bond distances and angles

The distances and angles in L-ascorbic acid may to a good approximation be discussed in terms of the average values, in spite of the small effects upon the angles as discussed above.

Generally, it may be said that the carbon–carbon distances which are found are in accordance with the accepted values for different hybridizations and agree well with the empirical formula given by Stoicheff (1962), as indicated in Fig. 3.

The largest variation in distances occurs in the C–O bonds. The double bond seems to be normal while the single bonds vary between 1.326 and 1.431 Å. Some of these variations may be attributed to the hybridizations of the carbon atoms, and the most striking example is the large difference in the C–O bonds in the rings (0.089 Å). This is usually found in lactone bridges and may be interpreted as being due to a valence resonance form

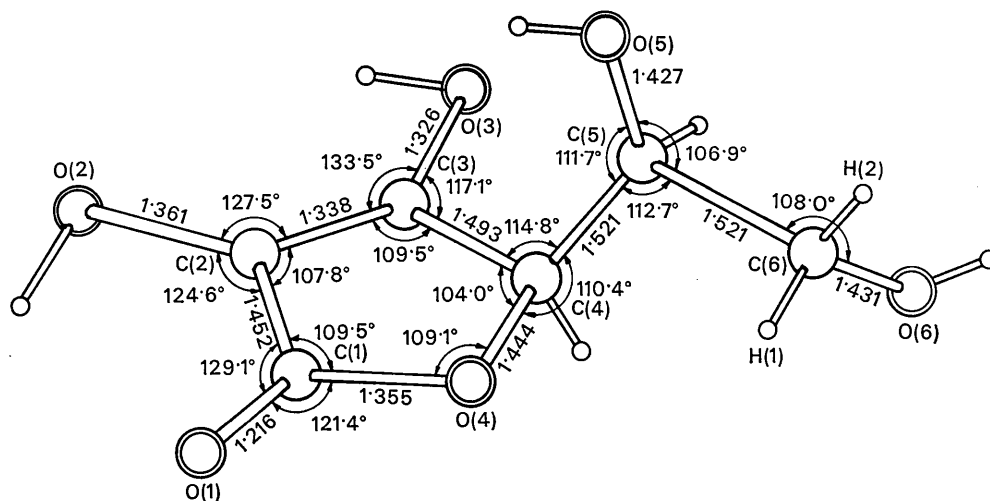
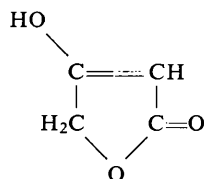


Fig. 2. Average values of bonding distances and angles.

Particular attention is called to the arrangement about the C(3) atom and to the difference in the C–O bonds in the endiol group. It is also a fact that L-ascorbic acid acts as a monoprotic acid, and by analogy to tetronic acid



there is little doubt that the hydrogen atom attached to O(3) is the protolytic one. In α -methyltetronic acid MacDonald & Alleyne (1963) report an extremely short C–O distance (1.24 Å), and even in L-ascorbic acid the corresponding C–O distance is as short as 1.326 Å. Vitamin C may be considered as a γ -substi-

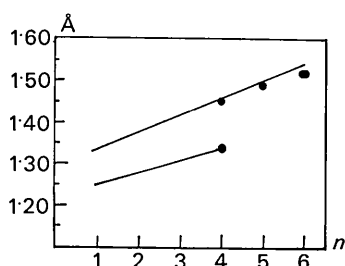


Fig. 3. Diagram showing the empirical C–C (upper line) and C=C distances as functions of the number of adjacent bonds according to Stoicheff (1962). Experimental results for L-ascorbic acid are indicated by dots.

tuted α -hydroxytetronic acid, but tetronic acid is somewhat stronger and has $pK=3.76$ according to Haynes & Plimmer (1960). One should, however, also note that O(3) takes part in only one hydrogen bond, and it is difficult to decide whether the shortness in C(3)–O(3) relative to C(2)–O(2) is caused by this, or if the reason is the presence of such resonance forms as suggested by MacDonald & Alleyne and by Haynes & Plimmer. In α -D-glucose Brown & Levy (1965) report a C–O distance of 1.389 Å for a single-hydrogen-bonded oxygen atom, while the other C–O distances vary between 1.413 and 1.425 Å.

The internal angles in the five-membered ring have a mean value of about 108° , and it is obvious that the largest distortions occur in the angles about the double bond. The ring oxygen has a nearly normal angle of 109.1° , and with the obvious exception of the double bond, the distances and angles match quite well those found by Jeffrey, Rosenstein & Vlasse (1967) in D-galactono- γ -lactone. This molecule is quite similar to that of L-ascorbic acid, except for the double bond.

The hydrogen atoms

In order to study the hydrogen atoms a Fourier synthesis was calculated with the coefficients $F_{\text{obs}} - F(\text{C} + \text{O})_{\text{calc}}$. This gave the approximate centres of the electron density of the hydrogen atoms. The H positions are slightly distorted relative to the nuclear centres, partly because the phases of F_{obs} are based upon the heavy atoms only. Fig. 4 shows a composite drawing of the differential electron density as viewed

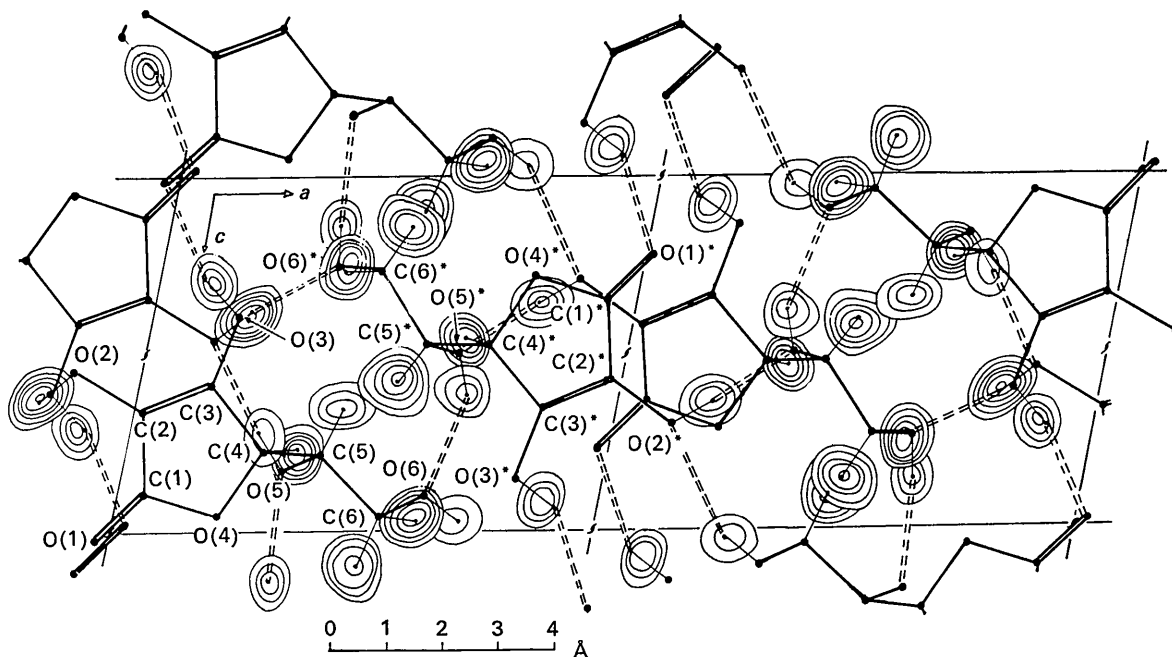


Fig. 4. Composite three-dimensional differential electron density showing the hydrogen distribution as seen along [010]. Contours at intervals of $0.1 \text{ e.}\text{\AA}^{-3}$, starting at $0.2 \text{ e.}\text{\AA}^{-3}$. Small dots indicate hydrogen positions found by neutron diffraction. Doubly stippled lines indicate hydrogen bonds.

along [010]. The dots indicate the hydrogen positions found by neutron diffraction, while the density maxima are very nearly coincident with those found by least-squares refinement of the X-ray data. This discrepancy is demonstrated more clearly in Fig. 5 which shows the residual electron density along the C-H and O-H bonds.

During the least-squares refinement it was noted that the B values for the H atoms were unsatisfactory because they agreed neither with the neutron diffraction results nor with the amplitudes of the C and O atoms to which they were attached. Some were even negative. This effect has been observed by several authors, and the trouble seems to arise from the erroneous form factor used for this atom. Up to now, this function has been determined by the $1s$ orbital of the isolated hydrogen atom, but Steward, Davidson & Simpson (1965) have shown that a better form factor results by

using a spherical approximation to the bonded hydrogen atom in the hydrogen molecule. The result is a contraction of the $1s$ orbital, thus giving rise to a higher scattering power for the whole range of $\sin \theta/\lambda$. In the present case the application of the improved form factor led to an average increment in B of 2.49 \AA^2 (Table 8) which is close to the expected value. The effect on positional parameters was negligible, and only a very small improvement in R resulted.

A second very important point in their investigation is that 'within the spherical approximation for a bonded H atom, least squares will place the centre of the spherical representation to the density off the proton into the bond towards the heavy atom'. For a C-H bond this was calculated to be 0.092 \AA , while the comparison between the present X-ray and neutron results gave a value of 0.09 \AA . For the O-H bond the experimental value is 0.15 \AA , as may be seen from Fig. 6.

Table 8. *Thermal parameters for L-ascorbic acid*

All b_{ij} values are multiplied by 10^4 . Standard deviations are given in parentheses. For the H atoms the isotropic B values are given both for the McWeeny (1951) form factor and for the one given by Steward, Davidson & Simpson (SDS) (1965).

	b_{11}	b_{22}	b_{33}	b_{12}	b_{13}	b_{23}
O(1)	16 (1)	163 (8)	96 (5)	12 (5)	21 (3)	-15 (14)
O(2)	10 (1)	159 (7)	107 (5)	7 (5)	2 (3)	-4 (14)
O(3)	15 (1)	189 (8)	77 (5)	7 (5)	12 (3)	46 (14)
O(4)	14 (1)	177 (8)	72 (5)	1 (5)	10 (3)	-38 (13)
O(5)	21 (1)	107 (7)	131 (7)	-17 (5)	-1 (4)	0 (13)
O(6)	15 (1)	205 (10)	151 (7)	-40 (5)	-9 (4)	100 (14)
O(1)*	15 (1)	183 (8)	98 (5)	-2 (5)	24 (3)	27 (15)
O(2)*	11 (1)	175 (9)	100 (5)	-9 (5)	1 (3)	13 (14)
O(3)*	17 (1)	266 (10)	77 (5)	19 (6)	21 (3)	-43 (16)
O(4)*	11 (1)	155 (7)	76 (5)	-9 (5)	10 (3)	47 (13)
O(5)*	18 (1)	83 (6)	135 (6)	15 (4)	28 (4)	18 (12)
O(6)*	14 (1)	131 (8)	133 (6)	16 (4)	8 (3)	62 (12)
C(1)	13 (1)	99 (9)	92 (7)	11 (6)	16 (4)	12 (17)
C(2)	12 (1)	97 (8)	77 (6)	1 (6)	6 (4)	13 (16)
C(3)	12 (1)	101 (8)	80 (7)	7 (6)	1 (4)	-6 (16)
C(4)	13 (1)	134 (10)	80 (7)	-8 (6)	16 (4)	4 (17)
C(5)	14 (1)	101 (9)	100 (8)	6 (5)	16 (5)	-10 (14)
C(6)	15 (1)	152 (10)	114 (8)	-20 (6)	5 (4)	48 (17)
C(1)*	12 (1)	86 (8)	102 (7)	-5 (6)	10 (4)	-20 (17)
C(2)*	14 (1)	89 (8)	100 (7)	-9 (6)	8 (4)	13 (16)
C(3)*	16 (1)	121 (8)	76 (7)	-6 (6)	13 (4)	-33 (16)
C(4)*	13 (1)	112 (10)	90 (7)	7 (6)	12 (4)	7 (16)
C(5)*	12 (1)	108 (9)	102 (8)	3 (5)	24 (4)	34 (15)
C(6)*	12 (1)	131 (9)	111 (8)	-3 (6)	3 (4)	-11 (15)
			McWeeny	SDS		
O(2) H			-0.5 (6)	1.9 (6)		
O(3) H			2.0 (9)	4.8 (9)		
O(5) H			4.3 (12)	7.5 (13)		
O(6) H			2.3 (9)	5.0 (10)		
O(2)*H			0.6 (7)	3.0 (8)		
O(3)*H			6.4 (15)	9.6 (16)		
O(5)*H			3.0 (10)	5.9 (11)		
O(6)*H			3.4 (11)	6.3 (12)		
C(4) H			-1.0 (6)	1.1 (6)		
C(5) H			-0.2 (7)	1.8 (7)		
C(6) H(1)			0.1 (7)	2.4 (8)		
H(2)			-0.4 (7)	1.8 (7)		
C(4)*H			0.0 (7)	2.2 (7)		
C(5)*H			-1.2 (6)	0.9 (6)		
C(6)*H(1)			-1.8 (5)	0.4 (7)		
H(2)			-0.7 (6)	1.6 (7)		

Hydrogen bonding

As seen from Fig. 4, the hydrogen bond system consists of four sequences which involve the following atoms:

- (1) $\cdots O(5) - H \cdots O(2') - H \cdots O(6)^* - H \cdots O(5') - H \cdots$
- (2) $\cdots O(5)^* - H \cdots O(6) - H \cdots O(2')^* - H \cdots O(5')^* - H \cdots$
- (3) $O(3) - H \cdots O(1)$
- (4) $O(3)^* - H \cdots O(1)^*$

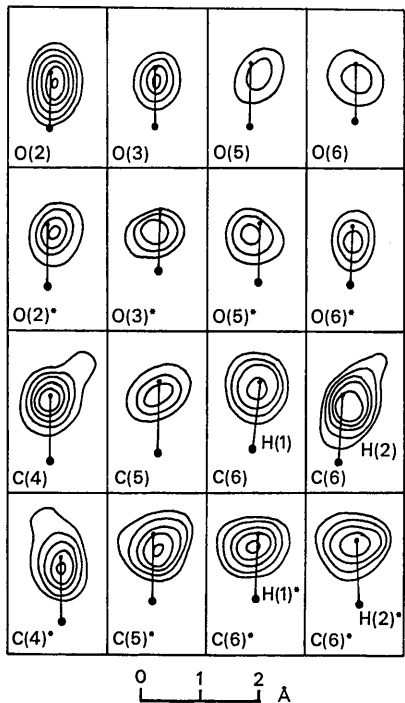


Fig. 5. Electron density of hydrogen along the different O-H and C-H bonds. Dots indicate the H positions found by neutron diffraction.

It should be noted that the asterisk refers to an atom in molecule *B*, and that the prime refers to symmetry equivalents of *A* and *B*.

Sequences (1) and (2) generate helices running along [001] and these are situated at an elevation slightly below the planes of the rings, while sequences (3) and (4) are isolated and lie close to the same planes.

No intramolecular hydrogen bond occurs, and the oxygen atom within the ring is the only one which does not take part in this kind of bonding. In each molecule three oxygen atoms act both as donor and acceptor, one as donor only and one as acceptor only.

To illustrate the environments of the two independent molecules they are drawn side by side in Fig. 7, and the angles and distances involving all hydrogen atoms are given in Table 9. Note that except for $O(3) \cdots O(1)$ and $O(3)^* \cdots O(1)^*$ the donor-acceptor sequence is reverse in the two molecules, and that the hydroxyl groups in the enediol system afford shorter $O \cdots O$ bonds than do the alcoholic OH groups. The average is 2.645 Å *versus* 2.799 Å.

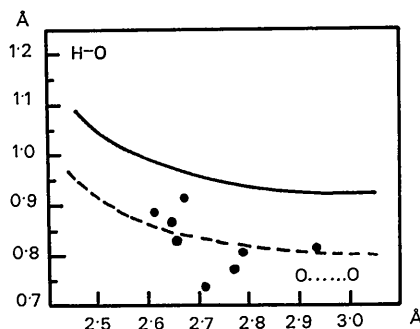


Fig. 6. Correlation diagram between the O-H and the $O \cdots O$ distances. The full curve represents the average of neutron diffraction results, the broken curve the best adapted curve for the present X-ray results.

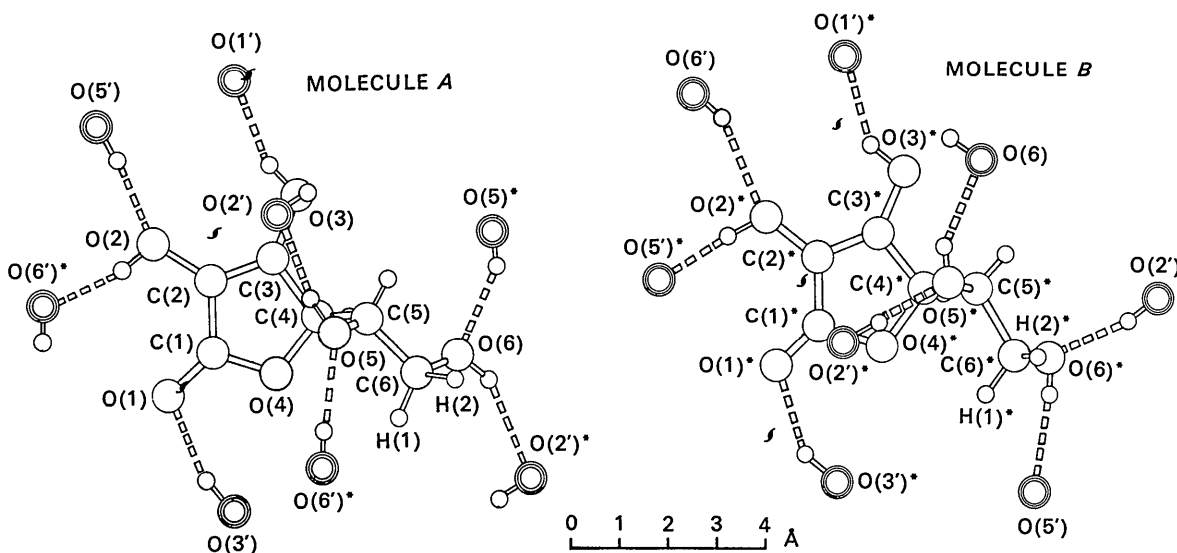


Fig. 7. Environments and hydrogen bonding for molecules *A* and *B*. Oxygen atoms in neighbouring molecules are indicated by triple circles.

The expected inverse relationship between the O—H and O...O distances seems to hold also in this case (Fig. 6), even if the above mentioned correction for the actual O—H distances seems appropriate. In addition to this a correction for anisotropic movements of the hydrogen atoms would be desirable, but this has not been undertaken for the X-ray case.

There is also a tendency to larger deviation from linearity in the O—H...O bond as the O...O distance increases.

Thermal parameters

The thermal parameters b_{ij} given in Table 8 have been used to calculate the main axes for the vibrational el-

lipsoids. From the shapes of these ellipsoids it may be stated that the atoms generally have their largest amplitudes along [010]. The carbon atoms have smaller root mean square amplitudes than the oxygen atoms that are attached to them, and also a smaller degree of anisotropy. There are also some indications of libration centres in the middle of the five-membered rings, but no corrections have been made for these effects.

Residual electron density

At the final stage of refinement a three-dimensional difference synthesis including all atoms was calculated in order to detect any residual electron density. Areas

Table 9. Distances (Å) and angles involving hydrogen atoms

Bond	The asterisk refers to molecule B.				
	O—H	H...O	O...O	∠O—H...O	∠C—O—H
O(2)—H...O(6)*	0.89 (2)	1.75 (2)	2.612 (3)	165 (3)°	112 (2)°
O(2)*—H...O(5)*	0.87 (3)	1.77 (3)	2.645 (3)	179 (3)	115 (2)
O(3)—H...O(1')	0.83 (3)	1.87 (4)	2.656 (3)	158 (3)	113 (2)
O(3)*—H...O(1')*	0.92 (4)	1.84 (5)	2.666 (3)	148 (4)	107 (3)
O(5)—H...O(2')	0.81 (4)	2.01 (5)	2.786 (4)	160 (5)	104 (4)
O(5)*—H...O(6)	0.74 (4)	2.05 (4)	2.707 (4)	149 (4)	100 (4)
O(6)—H...O(2')*	0.82 (3)	2.23 (4)	2.935 (3)	144 (3)	111 (3)
O(6)*—H...O(5')	0.77 (5)	2.02 (5)	2.769 (4)	162 (4)	114 (3)
	C—H	∠C(3)—C(4)—H	∠C(5)—C(4)—H	∠O(4)—C(4)—H	
C(4)—H	1.10 (3)	111 (2)°	107 (1)°	109 (1)°	
*	1.03 (4)	112 (2)	109 (2)	106 (2)	
		∠C(4)—C(5)—H	∠C(6)—C(5)—H	∠O(5)—C(5)—H	
C(5)—H	0.95 (3)	107 (2)°	109 (2)°	111 (2)°	
*	1.01 (3)	105 (2)	109 (1)	110 (2)	
		∠C(5)—C(6)—H	∠O(6)—C(6)—H	∠H(1)—C(6)—H(2)	
C(6)—H(1)	1.00 (3)	113 (2)°	109 (2)°	108 (3)°	
*	0.98 (2)	111 (1)	114 (2)	107 (2)	
C(6)—H(2)	1.02 (3)	117 (2)	101 (2)		
*	1.05 (3)	112 (2)	105 (2)		

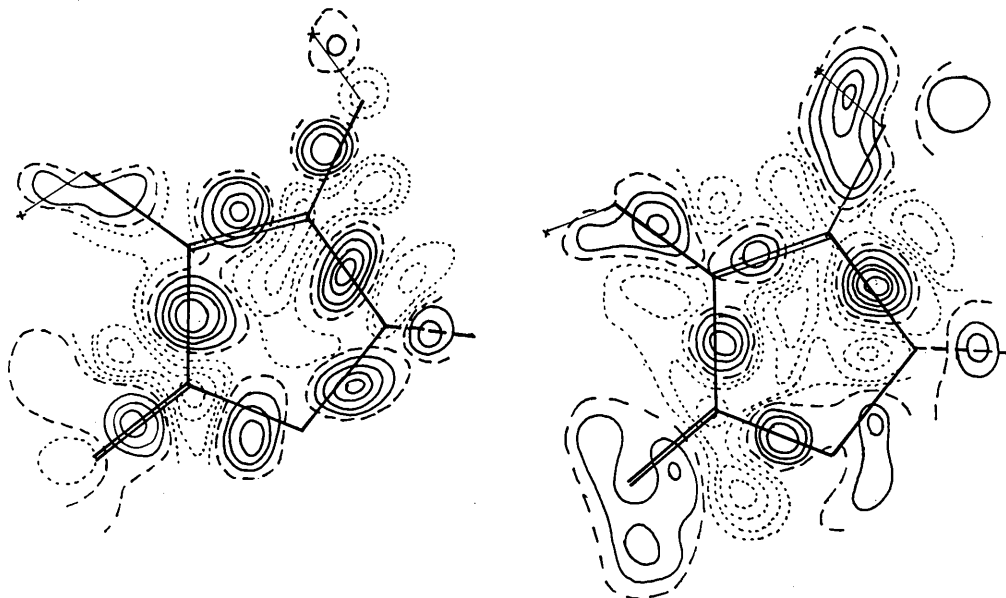


Fig. 8. Residual electron density in the planes of the rings. Zero contours are broken, negative are dotted. Contours at intervals of 0.05 e.Å^{-3} .

of low negative and positive density were found throughout the unit cell, but the interesting fact remains that the highest peaks were found in the spaces between the heavy atoms. This is particularly the case for the C-C bonds, while the terminal C-O bonds in the side chains have very small or absent residuals. To illustrate the situation the residual electron density in the planes of the rings is shown in Fig. 8. Similar effects have been reported by Hartman & Hirshfeld (1966) and have been more thoroughly discussed by O'Connell, Rae & Maslen (1966).

The writer is glad to have this opportunity of thanking Prof. O. Hassel and Prof. S. Furberg for the use of experimental equipment and for their kind interest in this work. I also owe C. Rømming and B. Klewe my gratitude for their advice and criticism, and A. Hordvik for encouraging discussions.

The financial support of Nansenfondet and of Norges Almenvitenskapelige Forskningsråd is gratefully acknowledged.

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The Use of Neutron Anomalous Scattering in Crystal Structure Analysis. I. Non-Centrosymmetric Structures

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(Received 21 November 1966 and in revised form 6 March 1967)

A method for solving the phase problem *ab initio* in crystal structure studies by neutron diffraction has been suggested. This method is based on the anomalous scattering of thermal neutrons by certain nuclei. Using the data collected at two neutron energies, the process of phase determination is carried out in two steps: (i) the location of the position of the anomalous scatterer and (ii) the correlation of the phase of the structure factor with the phase of the anomalous scatterer. The method gives unique solution of the phases. The expressions deduced are general and can be used for X-ray anomalous scattering also.

1. Introduction

Direct methods of sign determination* which are based on the positivity of scattering matter are not applicable to neutron diffraction. Nor can the heavy atom method be used, as the scattering lengths of various nuclei do not differ appreciably. For these reasons the use of neutron diffraction in crystallography has been restricted to the location and the refinement of position

of light atoms (from the point of view of X-ray scattering) in a structure for which the main features are known from X-ray diffraction work. The possibility of solving the phase problem *ab initio* in neutron diffraction studies stems from the fact that some nuclei (e.g. ^{113}Cd , ^{149}Sm , ^{151}Eu and ^{157}Gd) show anomalous scattering in the thermal neutron range (Peterson & Smith, 1961, 1962). Ramaseshan (1966) pointed out that anomalous dispersion effects in neutron scattering are much more pronounced than in X-ray scattering and hence can be used effectively in solving the structures provided the

* See a recent paper by Karle (1966).