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The Crystal Structure of Cyclohexane-1,1′-diacetic Acid

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Cyclohexane-1,1′-diacetic acid crystallizes in the monoclinic system, space group *Cc*, $a=13\cdot785$, $b=8\cdot151$, $c=10\cdot558$ Å and $\beta=121°2'$. A portion of the molecule corresponding to a pseudo *C*2 symmetry has been located by a direct method. The structure has been refined by least-squares procedures to $R=0\cdot060$ for 774 reflexions measured with an automated diffractometer. The carbon atoms of the molecule are arranged in a diamond-like structure. The interactions between the side groups and the cyclohexane ring lead to deviations of the bond and rotation angles from their normal value. Both the non-equivalent C=O groups are in *syn*-planar orientation with respect to the C_α–C_β bonds. Infinite chains of hydrogen-bonded molecules are formed along the $\mathbf{a}+\mathbf{c}$ direction.

Introduction

The effect of bulky substituents on the conformation of cyclohexane rings has been studied by several authors (Eliel, 1962; Hanack, 1965; Eliel, Allinger, Angyal & Morrison, 1965; Lambert, Carhart & Corfield, 1969). A comparative analysis of the conformational effects of axial and equatorial substituents is expecially interesting. For this reason, in connexion with our structural studies on dicarboxylic acids, we have performed single-crystal X-ray analyses of the 1,2-*cis* (Benedetti, Pedone & Allegra, 1970) and 1,2-*trans* (Benedetti, Corradini, Pedone & Post, 1969; Benedetti, Corradini & Pedone, 1969) (racemic and optically active forms) cyclohexane-dicarboxylic acids. In the present paper we will describe the crystal structure of a cyclohexane derivative bearing two identical substituents on the same site, namely cyclohexane-1,1′-diacetic acid (CDA).

Experimental

CDA was purchased from Matheson Coleman and Bell. Single crystals were obtained from acetone solutions by slow evaporation. On the basis of preliminary Weissenberg photographs (Cu *Kα* radiation) the crystals were found to belong to the monoclinic system. The systematic absences indicate *C*2/*c* or *Cc* as possible space groups. The cell dimensions were determined from a least-square fitting of the setting angles of twelve reflexions ($2\theta>90°$) and are reported in Table 1. The collection of the intensities was performed with a Picker four-circle automated diffractometer equipped with a PDP-8 digital computer. The θ–2θ scan mode with Ni-filtered Cu *Kα* radiation ($\lambda=1\cdot5418$ Å) and pulse height analysis were used; a total of 774 independent reflexions were collected in the range of 2θ explored (0–130°). Two stationary-crystal stationary-counter background counts of 10 sec were taken at each end of each scan.

Table 1. *Unit-cell dimensions*

Cyclohexane-1,1′-diacetic acid, $C_{10}H_{16}O_4$, M.W. 200·24
Monoclinic, space group *Cc*, $Z=4$, $F(000)=432$

$a=13\cdot785\pm0\cdot008$ Å
$b=\ \ 8\cdot151\pm0\cdot003$
$c=10\cdot558\pm0\cdot007$
$\beta=121°2'\pm15'$

$d_{calc}=1\cdot308$ g.cm^{-3}
$d_{exp}=1\cdot30$ g.cm^{-3} (flotation method)

Structure determination and refinement

Generally, carboxylic acids tend to form a hydrogen bond system between carboxyl groups across crystallographic symmetry centres (Donohue, 1968); in view of this frequently observed behaviour, we first considered the possibility that the space group was the centrosymmetric group *C*2/*c*. The presence of four molecules per unit cell (see Table 1), however, imposes the restriction that each molecule must be on a twofold crystallographic axis, ruling out at this stage the hypothesis of a statistically disordered arrangement.

Accordingly, possible molecular models containing a twofold axis were investigated; it was soon apparent that the cyclohexane ring had to be assumed to be in the 'skew-boat' conformation which is reported to be energetically unfavourable compared with the common chair form (5·5 kcal.mole^{-1} difference) (Eliel, 1962). However, the possibility could not be excluded that such an energy difference might be strongly reduced by interactions between the ring and the side groups. Consequently we have applied to the present case the symbolic addition procedure for the direct determination of the structure factor signs in the centrosymmetric *C*2/*c* space group. By taking into account all the reflexions with $|E|>1\cdot2$ and all the Sayre relations with $\tanh(|E_\mathbf{H}\cdot E_\mathbf{K}\cdot E_{\mathbf{H}+\mathbf{K}}|\sigma_3/\sigma_2^{3/2})>0\cdot83$, we were eventually

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able to express most of the signs as products of two basic signs. One of the four possible solutions gave rise to an electron density map, calculated with *ca.* 140 reflexions, where all the atoms of the molecule were clearly recognized except C(3), C(4) and C(5) (Fig. 1). It seemed remarkable that the geometrical parameters of the resulting part of the molecule were satisfactory and furthermore the centrosymmetric carboxyl groups of adjacent molecules were in the expected orientation which would result in infinite rows of hydrogen-bonded molecules (axis of the row parallel to $\mathbf{a}+\mathbf{c}$). A Fourier synthesis phased with the atoms already detected failed to show the three missing atoms in positions consistent with the $C2/c$ space group, and showed instead six peaks having approximately half the weight of the atoms previously located. Attempts to refine the structure in the $C2/c$ space group, assuming statistical disorder of the molecules with the cyclohexane ring in the chair conformation, were unsuccessful since the R value $(=\sum ||F_c|-|F_o||/\sum |F_o|)$ never dropped below 0·35. The Cc space group was therefore considered. All the atoms clearly detected in the first Fourier synthesis were retained and the molecular model completed with the three missing atoms in correct positions giving rise to a chair conformation for the cyclohexane ring (they were seen to correspond approximately with three of the half-weight peaks found previously). The R value immediately dropped below 0·20; six least-squares cycles, of which the last three were with anisotropic thermal factors, were sufficient to bring

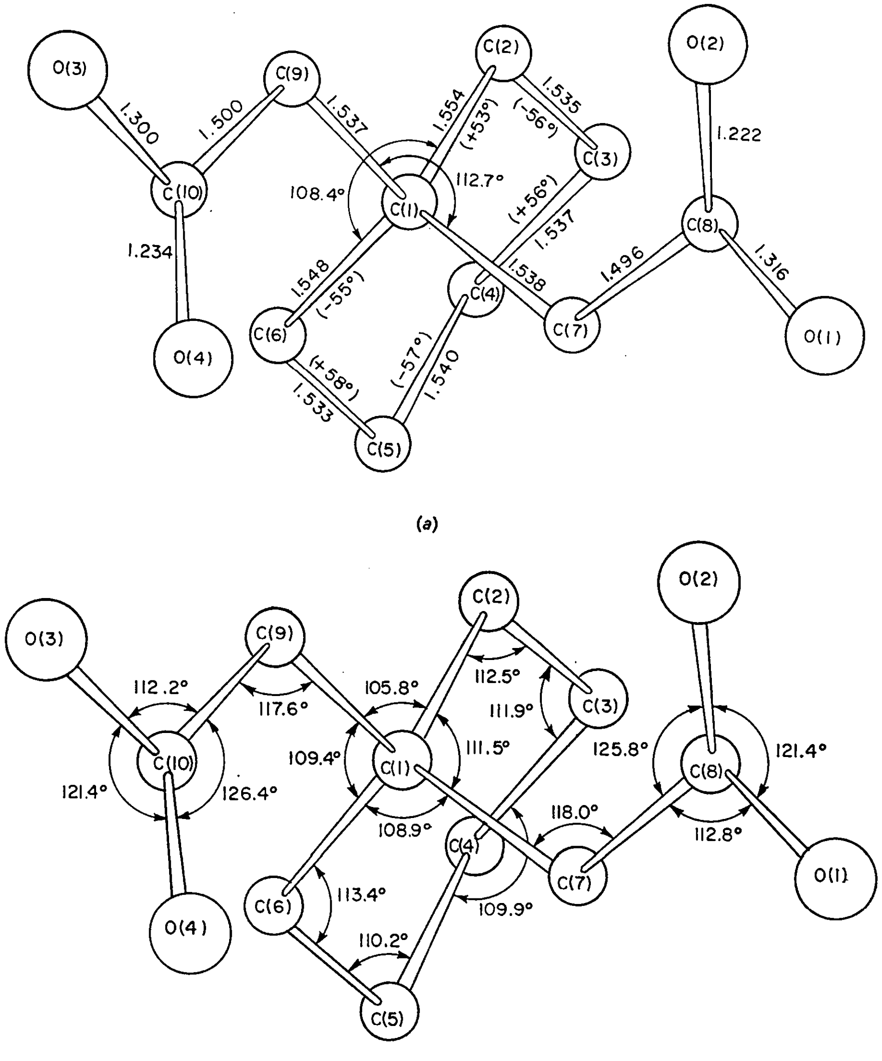

Fig. 1. Molecular model for cyclohexane-1,1'-diacetic acid. Bond lengths and rotation angles (in the ring) are reported in (*a*); valence angles are given in (*b*). The standard deviations for bond distances, bond angles and internal rotation angles are respectively 0·004 Å, 0·2° and 0·5°.

the disagreement index to 0·060 for the 774 measured reflexions. The hydrogen atoms were introduced before the last cycle in their stereochemically expected positions ($d_{\text{C–H}} = 1{\cdot}08, d_{\text{O–H}} = 1{\cdot}00$ Å, ∠C–H–C = 109·5 and ∠C–O–H = 120·0°) with an isotropic thermal factor equal to the average of the B_{ii} values of the carrier atoms. All the hydrogen atom parameters were kept fixed. In the final stage of the refinement process the weighting scheme suggested by Cruickshank & Pilling (1961) was adopted [$w(hkl) = 1/(a\,F_o^2 + b\,F_o + c)$]. A list of observed and calculated structure factors has been deposited as document No. 00532 NAPS with the American Society for Information Science.* In Table 2 the final atomic parameters are reported with their estimated standard deviations (Immirzi, 1967).

Discussion of the structure

The molecular geometry is shown in Fig. 1 and the internal rotation angles are given in Table 3. The mole-

Table 2. *Final atomic parameters*

(*a*) Positional parameters

	x	y	z
C(1)	0·0008 (4)	−0·1344 (5)	0·2492 (5)
C(2)	0·0514 (4)	−0·2554 (6)	0·3819 (5)
C(3)	0·1129 (5)	−0·4003 (7)	0·3609 (7)
C(4)	0·0356 (6)	−0·4941 (7)	0·2168 (8)
C(5)	−0·0114 (5)	−0·3759 (6)	0·0843 (6)
C(6)	−0·0740 (4)	−0·2332 (6)	0·1057 (5)
C(7)	0·0943 (3)	−0·0464 (5)	0·2369 (4)
C(8)	0·1712 (4)	0·0674 (5)	0·3590 (5)
C(9)	−0·0739 (4)	−0·0153 (6)	0·2747 (5)
C(10)	−0·1354 (4)	0·1157 (5)	0·1611 (5)
O(1)	0·2431 (0)	0·1439 (5)	0·3327 (0)
O(2)	0·1717 (4)	0·0892 (5)	0·4738 (4)
O(3)	−0·2031 (3)	0·2001 (5)	0·1875 (4)
O(4)	−0·1265 (3)	0·1451 (4)	0·0529 (4)
H(1)C(2)	0·090	−0·181	0·498
H(2)C(2)	−0·037	−0·305	0·405
H(1)C(3)	0·175	−0·381	0·392
H(2)C(3)	0·088	−0·499	0·332
H(1)C(4)	0·098	−0·601	0·159
H(2)C(4)	−0·028	−0·537	0·253
H(1)C(5)	−0·071	−0·456	−0·039
H(2)C(5)	0·075	−0·335	0·068
H(1)C(6)	−0·137	−0·249	0·122
H(2)C(6)	−0·095	−0·148	-0·006
H(1)C(7)	0·166	−0·119	0·200
H(2)C(7)	0·077	0·029	0·122
H(1)C(9)	−0·136	−0·086	0·282
H(2)C(9)	−0·022	0·066	0·360
H(1)O(1)	0·313	0·195	0·387
H(1)O(3)	−0·247	0·263	0·175

(*b*) Anisotropic thermal parameters*

	B_{11}	B_{22}	B_{33}	B_{12}	B_{13}	B_{23}
C(1)	3·0 (2)	2·7 (2)	2·5 (2)	0·1 (1)	1·4 (1)	0·3 (1)
C(2)	3·9 (2)	3·5 (2)	3·0 (2)	0·4 (2)	1·7 (2)	0·9 (1)
C(3)	3·7 (2)	3·5 (2)	5·6 (3)	0·6 (2)	1·7 (2)	0·7 (2)
C(4)	5·7 (3)	3·4 (2)	5·9 (3)	0·6 (2)	2·2 (2)	−0·3 (2)
C(5)	5·0 (3)	3·6 (2)	4·5 (3)	−0·2 (2)	1·9 (2)	−1·2 (2)
C(6)	3·1 (2)	3·4 (2)	3·3 (2)	−0·4 (1)	1·2 (1)	−0·5 (1)
C(7)	3·1 (2)	3·0 (2)	2·8 (2)	−0·4 (1)	1·7 (1)	−0·3 (1)
C(8)	3·4 (2)	2·6 (2)	3·1 (2)	−0·0 (1)	1·5 (1)	0·1 (1)
C(9)	3·6 (2)	3·6 (2)	2·8 (2)	0·8 (1)	2·1 (2)	0·6 (1)
C(10)	3·3 (2)	2·5 (2)	2·7 (2)	−0·2 (1)	1·5 (1)	0·0 (1)
O(1)	4·9 (2)	4·8 (2)	4·0 (2)	−2·0 (1)	3·0 (1)	−1·3 (1)
O(2)	7·0 (2)	5·9 (2)	3·9 (2)	−3·2 (2)	3·5 (2)	−1·8 (1)
O(3)	5·2 (2)	5·2 (2)	4·0 (2)	2·1 (1)	3·1 (1)	1·1 (1)
O(4)	4·7 (2)	3·7 (1)	4·1 (2)	1·4 (1)	2·9 (1)	1·2 (1)

* Temperature factor in the form:

$$T = \exp\,[-\tfrac{1}{4}(B_{11}h^2a^{*2} + B_{22}k^2b^{*2} + B_{33}l^2c^{*2} + 2B_{12}hka^*b^* + 2B_{13}hla^*c^* + 2B_{23}klb^*c^*)]\,.$$

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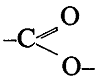
cule contains a pseudo-twofold axis which relates all atoms but C(3), C(4) and C(5): in the unit cell the molecules are oriented in such a way that the pseudo-symmetry axis is parallel to **b**, which accounts for the resulting pseudo-*C*2/*c* symmetry. Some important features of the structure are:

(i) The diamond-like conformation of the carbon atoms of the molecule (see Fig. 1 and Table 3), which is best illustrated by the fact that all the dihedral angles involving carbon atoms are close to the staggered value (180, ± 60°). It is well known that these arrangements often represent the most stable conformations for saturated hydrocarbon molecules. In the present case the molecule may assume four different diamond-like conformations, essentially equivalent in terms of intramolecular energy (*i.e.* all of them have the same number of *gauche trans* rotation angles and also practically the same intramolecular interactions). These conformations are pairwise mirror images (see Fig. 2). No other diamond-like conformation can avoid *syn*-diaxial C---C intramolecular contacts. Packing effects are probably responsible for the choice of conformation (*a*) in Fig. 2.

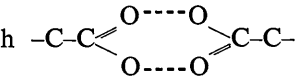
(ii) The existence of deviations of some bond and dihedral angles from their normal value, the distortions cooperating to release the intramolecular interactions between the acetic group and the cyclohexane ring. These deformations are: (*a*) the increase in the C(1)–C(7)–C(8) and C(1)–C(9)–C(10) angles (117·8 ± 0·2°) compared with the corresponding value of 115·4 ± 1·0°, the average of other recent structural determinations of aliphatic acids (Housty & Hospital, 1964, 1965, 1966; Strieter & Templeton, 1962); (*b*) the decrease in the absolute value of the ring rotation angles around C(6)–C(1) and C(1)–C(2) (−55 and +53° respectively compared with an average of 57 ± 1° for the other 4 rotation angles of the ring) which leads to a flattening of the ring in the vicinity of C(1); (*c*) the decrease of the C(2)–C(1)–C(9) angle (105·8°) with respect to the tetrahedral value (109·5°); (*d*) the disparity between the C(9)–C(1)–C(6) and C(9)–C(1)–C(2) angles (109·4 and 105·8° respectively).

(iii) The nearly *syn*-planar orientation of both C–O bonds with respect to the C_α–C_β bond; this conformation has been observed in a number of carboxylic acids (Dunitz & Strickler, 1966, 1968; Benedetti, Corradini, Pedone & Post, 1969; Benedetti, Corradini & Pedone, 1969). As a result (Fig. 3) the shortest O---C intramolecular distances between atoms separated by four or more bonds are 3·05 Å [O(2)–C(9) and O(4)–C(7)] and 3·15 Å [O(2)–C(3) and O(4)–C(5)]. The two non-equivalent O---O hydrogen-bond distances do not depart appreciably from the normal values (2·65 ± 0·02 and 2·70 ± 0·02 Å respectively). The two



$-\mathrm{C}{<}\genfrac{}{}{0pt}{}{\mathrm{O}}{\mathrm{O}-}$

facing groups are approximately coplanar (least-squares equation $0{\cdot}5111x - 0{\cdot}7144y + 0{\cdot}1460z - 1{\cdot}3890 = 0$; mean-square distance = 0·040 Å), while the C_α atoms depart appreciably from the least-squares plane through



$-\mathrm{C}-\mathrm{C}{<}\genfrac{}{}{0pt}{}{\mathrm{O}\cdots\cdots\mathrm{O}}{\mathrm{O}\cdots\cdots\mathrm{O}}{>}\mathrm{C}-\mathrm{C}-$

(least-squares equation $0{\cdot}5129x - 0{\cdot}7086y + 0{\cdot}1508z - 1{\cdot}3965 = 0$; the distances of C(7) and C(9) from this plane are 0·09 and 0·13 Å respectively).

(iv) In Fig. 3 a view of the crystal packing along the *b* axis is presented. The shortest inter- and intramolecular contacts are also reported: the latter occur in pairs to within a few hundreds of Å except for the contacst involving the C(3), C(4) and C(5) atoms. The structure consists of hydrogen-bonded rows along the **a** + **c** direction, the hydrogen bond being realized between carboxylic groups of molecules related by the glide plane.

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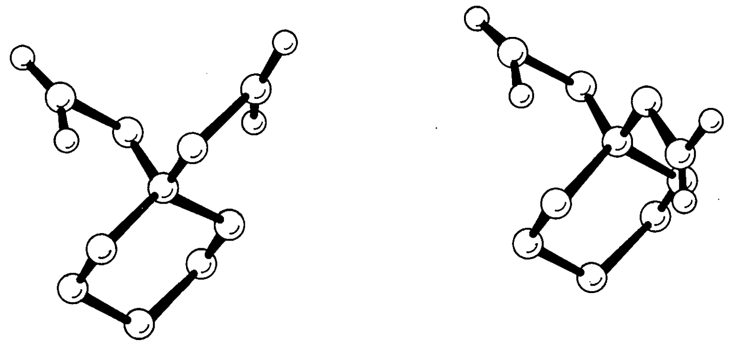

(*a*) (*b*)

Fig. 2. The two different diamond-like conformations available to the molecule. (*a*) corresponds to the actual conformation found in the present investigation.

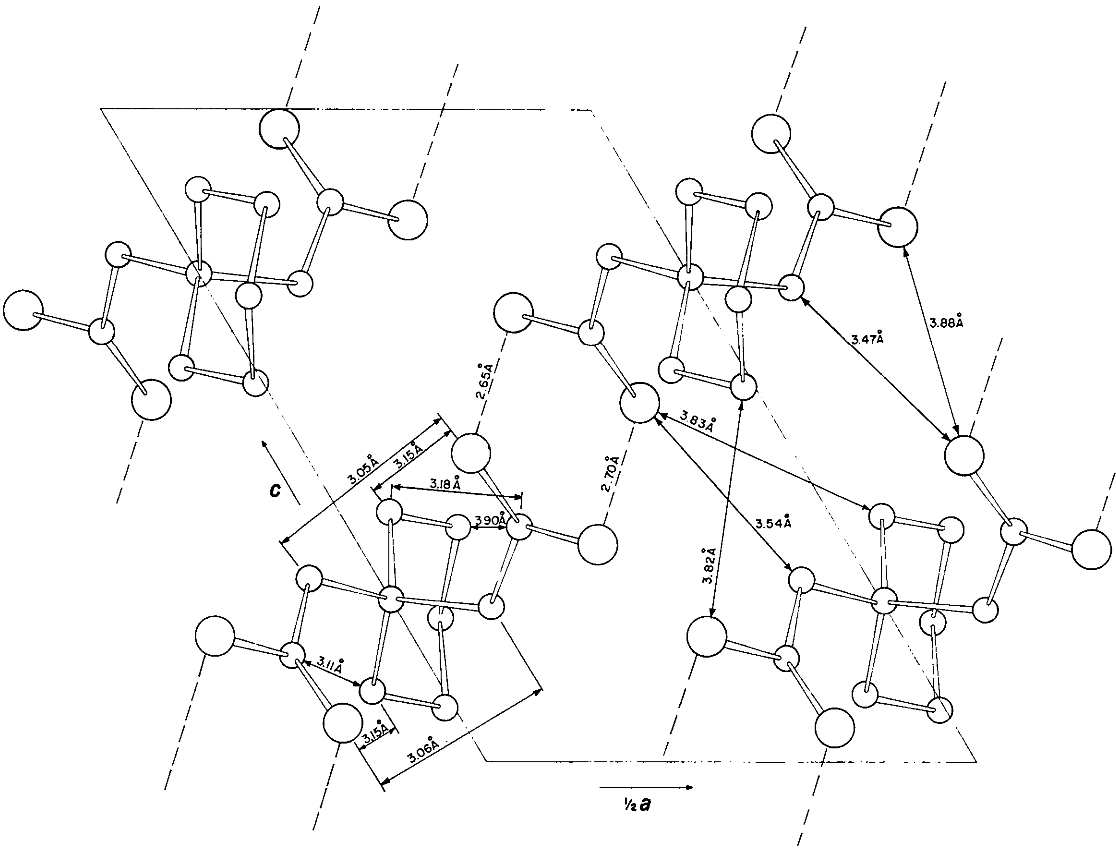

Fig. 3. Mode of packing of cyclohexane-1,1′-diacetic acid along (010). The shortest intermolecular and intramolecular contacts are indicated together with the hydrogen bond distances (dashed lines).

Table 3. *Internal rotation angles**

(*trans* conformation = 180°)

C(1)—C(2)-C(3)—C(4)	−56·0°
C(2)—C(3)-C(4)—C(5)	56·4
C(3)—C(4)-C(5)—C(6)	−56·6
C(4)—C(5)-C(6)—C(1)	57·9
C(5)—C(6)-C(1)—C(2)	−55·0
C(6)—C(1)-C(2)—C(3)	53·3
C(7)—C(1)-C(6)—C(5)	66·4
C(7)—C(1)-C(2)—C(3)	−66·5
C(7)—C(1)-C(9)—C(10)	58·6
C(9)—C(1)-C(2)—C(3)	170·6
C(9)—C(1)-C(6)—C(5)	−170·0
C(9)—C(1)-C(7)—C(8)	53·6
C(8)—C(7)-C(1)—C(2)	−65·2
C(8)—C(7)-C(1)—C(6)	175·2
C(10)-C(9)-C(1)—C(2)	−169·3
C(10)-C(9)-C(1)—C(6)	−62·7
C(1)—C(7)-C(8)—O(1)	−175·9
C(1)—C(7)-C(8)—O(2)	5·2
C(1)—C(9)-C(10)-O(3)	174·6
C(1)—C(9)-C(10)-O(4)	−5·2

* The exstimated standard deviation (average) is 0·7°.

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