

## Studies in molecular structure, symmetry and conformation I

### CRYSTAL AND MOLECULAR STRUCTURE OF 1-AMINOCYCLOOCTANE CARBOXYLIC ACID HYDROBROMIDE\*

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#### Abstract

Crystals of 1-aminocyclooctanecarboxylic acid hydrobromide are orthorhombic, with  $a = 26.026$ ,  $b = 7.087$ ,  $c = 6.149$ ,  $Z = 4$  and space group  $P2_12_12_1$ . The structure was solved in projections by direct methods and later refined with three-dimensional data using a full-matrix least-squares treatment. All hydrogen atoms were located from a difference Fourier and the final  $R$  factor for the 1128 observed reflections was 8.62%. The molecules are held together by a series of hydrogen bonds in a three-dimensional network. A detailed discussion of the intramolecular and the intermolecular features of the structure is presented. The cyclooctane ring is found to exist in the *boat-chair* conformation.

#### Introduction

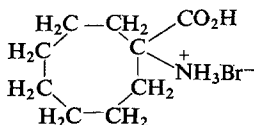
X-ray structural investigations of the cycloalkanes and their derivatives have been undertaken in this laboratory with a view to obtaining precise structural and conformational features of the ring systems. The compounds used for investigations were mainly 1-aminocycloalkanecarboxylic acid derivatives with five to eight atoms in the cycloalkane ring. Detailed, systematic X-ray studies of these common ring systems do not appear to have been made, although medium and larger ring systems have been studied (Dunitz & Venkatesan, 1961; Dunitz & Mayer, 1965; Brown, 1966; Müller, 1933; Bryan & Dunitz, 1960).† Recently, the cycloalkane ring system has been the subject of considerable theoretical investigation, and different groups of workers have elucidated the structure and conformation of these molecules from energy considerations. Also, by investigating such aminocarboxylic acid derivatives, valuable information is obtained for structural and conformational correlation with simple amino acids and peptides which have been studied thoroughly and systematically in this laboratory (Ramachandran, 1962; Ramachandran *et al.*, 1963; Sasisekharan, 1962; Ramachandran & Lakshminarayanan, 1966).

In this paper, we report the crystal and molecular structure of 1-aminocyclooctanecarboxylic acid hydrobromide, (I). X-ray studies of the other members of this cycloalkane series will be reported

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† For a recent review article on the conformation of medium rings, see Dunitz (1968).

separately: the structures of 1-aminocycloheptanecarboxylic acid hydrobromide and 1-aminocyclohexanecarboxylic acid hydrochloride are presented in this journal; the structure of 1-amino-



(I)

cyclopentane carboxylic acid hydrobromide has been reported (Chacko *et al.*, 1967; Chandrasekharan *et al.*, 1968).

### Experimental

Crystals of  $C_9H_{18}NO_2Br$  suitable for X-ray studies were obtained by slow evaporation of an aqueous solution at room temperature. The crystals were very thin needles. Preliminary oscillation and rotation photographs taken with Cu  $K\alpha$  radiation showed that the crystals belonged to the orthorhombic system. The unit cell dimensions, space group and other data of this compound were obtained from Weissenberg and precession photographs. The systematic absences were found to be  $h00$  absent for  $h = 2n + 1$ ;  $0k0$  absent for  $k = 2n + 1$ ;  $00l$  absent for  $l = 2n + 1$ .

The unit cell parameters and other crystal data are as follows:  $a = 26.026 \pm 0.022$ ,  $b = 7.087 \pm 0.009$ ,  $c = 6.149 \pm 0.012$  Å;  $V = 1133$  Å<sup>3</sup>;  $Z = 4$ ;  $D_m = 1.473$  g cm<sup>-3</sup> (floatation in a mixture of bromoform and benzene);  $D_c = 1.453$  g cm<sup>-3</sup>;  $FW = 251.8$ ;  $\mu$  (Cu  $K\alpha$ ) = 52 cm<sup>-1</sup>; space group  $P2_12_12_1$ .

*Collection of intensity data.* Three-dimensional intensity data were collected by the multiple film equi-inclination Weissenberg technique; two crystals were used to collect the data. A needle of dimensions  $0.65 \times 0.15 \times 0.2$  mm<sup>3</sup> was used to record the levels  $hkl$ ,  $l = 0$  to 5, and a second crystal of dimensions  $0.95 \times 0.25 \times 0.30$  mm<sup>3</sup> was used to record the levels  $hkl$ ,  $k = 0$  to 6. Nickel-filtered Cu  $K\alpha$  radiation was used throughout. The intensities were measured visually with a calibrated set of intensities recorded from the same specimen, and were corrected for Lorentz and polarization factors and spot shape (Phillips, 1962). The intensities were placed on the absolute scale by layer-wise Wilson plots (Wilson, 1942). The intensities of about 870 reflexions with the  $b$  axis mounting and about 910 reflexions with the  $c$  axis mounting were estimated. In the initial stages of structure determination, an average of the two intensities was taken for reflexions which were measured twice, once in each mounting. During the final stages, accurate intensities were obtained by a correlation of the intensity data about two axes after correcting for the absorption effects which will be reported in a later section. The scale and the temperature factors were initially obtained from Wilson plots, but later refined by the least-squares method.

### Determination of the structure

A two-dimensional Patterson function using the  $hk0$  reflexions gave the  $x$  and  $y$  coordinates of the bromine atoms. The  $R$  factor defined by  $R = \sum ||F_o| - |F_c|| / \sum |F_o|$  was found to be 47.6%. From the  $h0l$  Patterson function, the  $x$  and  $z$  coordinates of the bromine atoms were found; the  $R$  factor for the bromine for the  $h0l$  projection was found to be 48%. From the coordinates of the bromine in the two projections, and also taking into account the relative shift of the origin found from the projection (Buerger, 1959), the three-dimensional coordinates were fixed uniquely. The  $R$  factor using the bromine atom in the structure factor calculation was 46.8% for the three-dimensional data. Since the  $y$  and  $z$  coordinates for the bromine are special, the bromine contributes to reflexions of the type

$h + k + l = 2n$  only, and consequently the bromine-phased three-dimensional Fourier had a spurious centring effect and the number of peaks in the Fourier was doubled. To overcome this, it was decided to attack the structure in the  $(hk0)$  and  $(h0l)$  centrosymmetric projections by direct methods.

#### Application of the direct method for sign determination in the $hk0$ projection

It is well known from the results of various workers (Sayre, 1952; Cochran, 1952; Zachariassen, 1952; Hughes, 1953; Hauptman & Karle, 1953; Cochran & Woolfson, 1955) that the signs of the reflexions  $\mathbf{H}$ ,  $\mathbf{H}'$  and  $\mathbf{H} + \mathbf{H}'$  are related by

$$S(\mathbf{H}') \cdot S(\mathbf{H} \pm \mathbf{H}') \simeq S(\mathbf{H}) \quad (1)$$

where the symbol  $\simeq$  means 'probably equal' and  $\mathbf{H}$  represents  $hkl$ . The probability of the sign relation holding good can be estimated, and it is well known that the probability has a high value when the magnitudes of the unitary structure factors involved in the triplet relation are large. The above relation was used to connect reflexions for which signs were already known from the contribution of the heavy atom with those of the unknown signs, and thereby signs of reflexions for which bromine did not contribute were deduced. The symmetry of the  $hk0$  projection is  $pgg$ , and there are four groups of reflections: (a) EE, (b) OO, (c) OE, and (d) EO, where EO means  $h$  even  $k$  odd, and so on. The signs of reflections of groups (a) and (b) are known, and were fused to determine those of groups (c) and (d). At first the unitary structure factors were calculated using the relation

$$|U(hk0)| = \frac{|F(hk0)|}{\sum f_j} \left[ \frac{\sum f_j^2}{\langle I \rangle} \right]^{1/2} \quad (2)$$

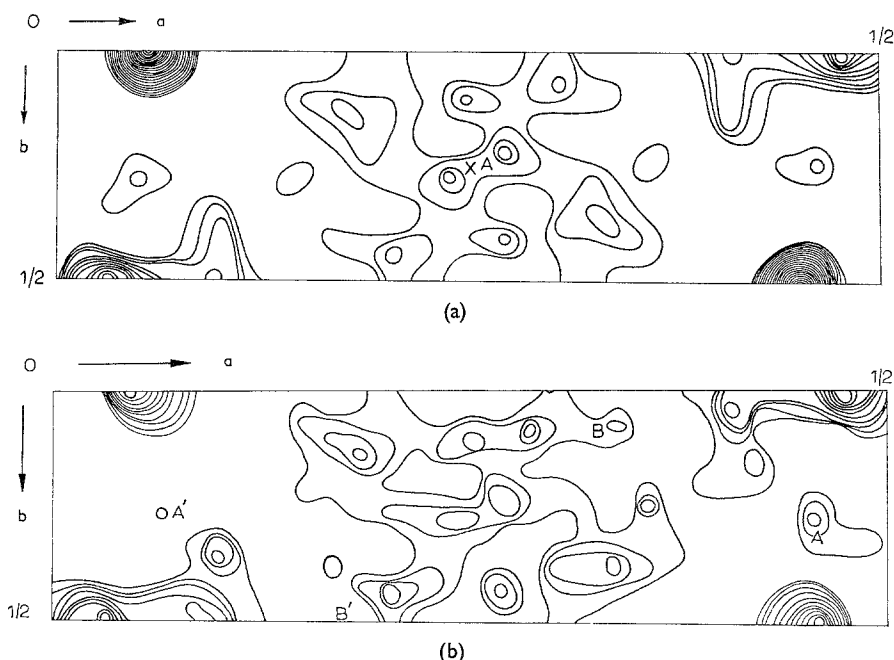


Fig. 1(a). Bromine-phased  $c$  axis Fourier projection. The point marked  $A$  is a spurious centre of inversion. (b) As for (a) but with a few additional signs for  $h + k = 2n + 1$  determined by direct methods. Contours are at arbitrary intervals.

where  $|F(hk0)|$  is the structure amplitude,  $\langle I \rangle$  is a local average intensity and  $f_j$  is the scattering factor of the  $j$ th atom. The factor in brackets gives the necessary correction to the temperature factor. The contribution from the bromine atoms were subtracted from the  $|F(hk0)|$  values for the reflexions of the type  $h+k$  even. Out of 95 reflexions belonging to this group, about 25 reflexions whose  $|U|$  values were greater than 0.2 were chosen as the basic set of known signs for propagation. Based on the sign of the reflexion 560 as +, we arrived at the signs of the following reflexions: 14,50 +; 16,50 +; 23,60 -; 26,30 -; 25,40 -; 21,40 +; 24,50 + and 940 +. The Fourier syntheses performed with the  $h+k$  even reflexions alone and with the above nine reflexions added to this group are shown in Figs. 1(a) and 1(b), respectively. Although the spurious symmetry was not broken completely, it may be noticed that some of the peaks [e.g. *A* and *B* in Fig. 1(b)] have higher densities than their mates [*A'* and *B'* in Fig. 1(b)]. This effect was most pronounced for peak *A*, and even this partial breaking of pseudo-symmetry was sufficient to fit a model. It is interesting to mention here that peak *A* later turned out to be the amino nitrogen atom. By a comparison of the peak heights in the Fourier maps, and choosing among the inversion pairs the ones which had higher density, a possible model was fitted, and the *R* factor was 31.7%. After four cycles of refinement on an IBM 1620, the *R* factor fell to 19.3%.

*Analysis of the b axis projection Fourier.* In a similar manner, the *b* axis projection Fourier also had a spurious symmetry, because bromine contributes to only the  $h+l$  even group of reflexions. Since the model had been refined to 19.3% in the other projection, it was thought unnecessary to repeat the sign determination procedure in this projection. With the knowledge of the common *x* coordinates a possible model was fitted in this projection and the *R* factor for the model was 42% for the  $h0l$  data. After four cycles of refinement, it fell to 22.6%.

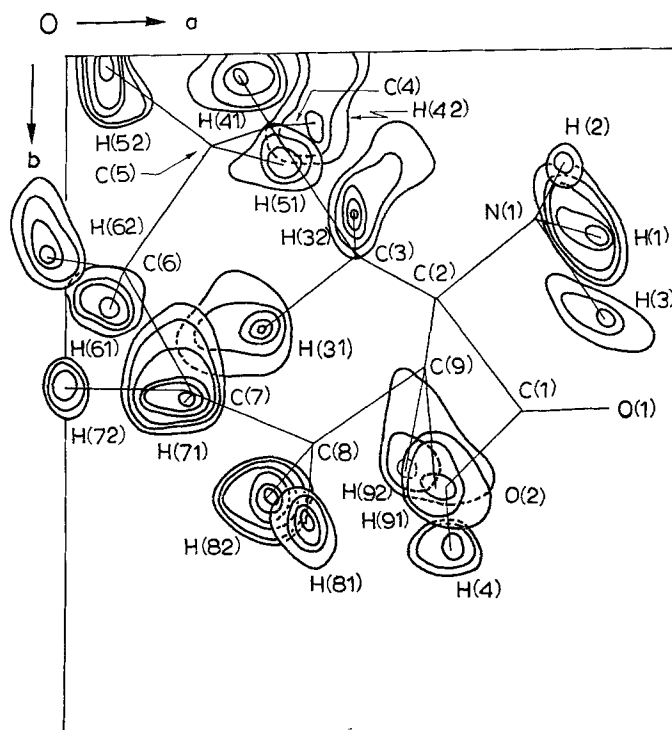


Fig. 2. Composite diagram of the final difference Fourier synthesis viewed along *c* axis, showing the hydrogen atoms. Contours are at  $0.1 \text{ e}/\text{\AA}^3$  with the initial contours at  $0.2 \text{ e}/\text{\AA}^3$ .

The projection refinements were stopped at this stage. Some of the atoms had fairly large temperature factors, indicating that appreciable adjustments might be required. The projection coordinates were the starting point for the three-dimensional refinement.

### Refinement of the structure

From the coordinates of the molecule in the two projections, an initial three-dimensional model was fitted. The  $R$  factor for the model was 39.6%; after two cycles of refinement with isotropic temperature factors using the LALS program on the CDC 3600, the  $R$  factor fell to 22.9%. At this stage a difference Fourier was computed, and corrections made in the coordinates of atoms C(1), C(3), C(4), C(5), C(7), C(8) and C(9) led to an  $R$  factor of 19.7%. Two more cycles of refinement with isotropic parameters for all the atoms reduced the  $R$  factor to 14.6%. The temperature factors for all atoms had stabilized at this stage and two more cycles of refinement with anisotropic thermal parameters for the bromine atom only gave  $R = 11.9\%$ .

A difference Fourier revealed all hydrogen atoms; the composite map viewed down the  $c$  axis is shown in Fig. 2. Around the amino nitrogen there were three peaks, indicating that the nitrogen is protonated. The densities of the hydrogen atoms varied from 0.4 to 0.8  $e/\text{\AA}^3$ . The  $R$  factor after inclusion of all the hydrogen atoms was 11.3%.

At this stage the temperature factors of all the atoms except C(1) were satisfactory, its value being 0.6  $\text{\AA}^2$ . It was felt that this could probably be due to the fact that the intensity data were not corrected for absorption effects. As was mentioned earlier, one of the crystals used had a  $\mu R \approx 1.6$ , and hence it was decided to correct for this and thus improve the data. The  $\mu R$  for the other crystal used in data collection was only 0.7, and hence absorption was neglected in this case. The intensity data collected about two axes were correlated by the method of Rollett and Sparks (1960). The function minimized was  $\sum_{\text{H}} s_i^c (F_{\text{H}}^c)^2 - s_j^b (F_{\text{H}}^b)^2$ , where  $s_i^c$  and  $s_j^b$  were the scale factors observed in the two cases and

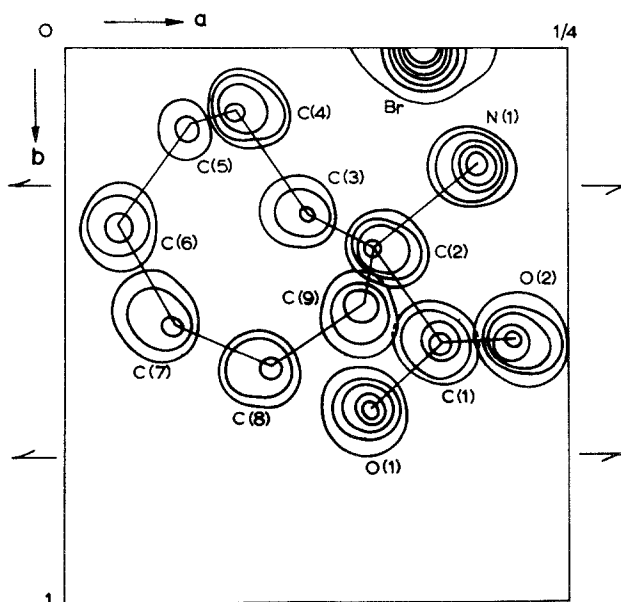


Fig. 3. Composite diagram of the final electron density function viewed along the  $c$  axis. Contours are at intervals of 2  $e/\text{\AA}^3$ . For bromine, the contour intervals are arbitrary.

$|F_{\mathbf{H}}^c|^2$  and  $|F_{\mathbf{H}}^b|^2$  were the observed intensities; the superscripts  $b$  and  $c$  refer to the axis about which the data were collected. With the hydrogen atoms and an ionic correction for the bromine atom, two

Table 1(a). *Positional and thermal parameters of the non-hydrogen atoms; esd ( $\times 10^4$ ) are given in parentheses*

Atom	$x$	$y$	$z$
O(2)	0.2223(3)	0.5334(13)	0.0234(16)
O(1)	0.1451(4)	0.6734(15)	0.0318(20)
C(1)	0.1786(5)	0.5383(19)	0.0870(20)
C(2)	0.1566(4)	0.3969(13)	0.2462(20)
C(3)	0.1115(4)	0.2917(18)	0.1385(28)
C(4)	0.0877(5)	0.1168(22)	0.2548(21)
C(5)	0.0594(5)	0.1498(23)	0.4646(28)
C(6)	0.0240(5)	0.3305(23)	0.4764(26)
C(7)	0.0457(5)	0.4972(26)	0.5810(26)
C(8)	0.0926(5)	0.6117(20)	0.4781(22)
C(9)	0.1444(5)	0.4926(20)	0.4695(20)
N(1)	0.1999(3)	0.2521(14)	0.2824(15)
Br	0.3074(0)	-0.0066(2)	0.2576(2)

more cycles of refinement with the correlated intensities reduced the  $R$  factor to 9.6%. Finally, two more cycles of refinement with anisotropic thermal vibrations for all the non-hydrogen atoms (with hydrogen included in the calculated structure factor only) gave  $R = 8.62\%$ . The final electron density viewed down the  $c$  axis is shown in Fig. 3.

The coordinates of the atoms, their standard deviations and anisotropic thermal parameters are given in Tables 1(a) and 1(b), and the positions of the hydrogen atoms are given in Table 1(c).

Table 1(b). *Positional and thermal parameters of the non-hydrogen atoms, esd ( $\times 10^4$ ) are given in parentheses*

Atom	$B_{11}$	$B_{22}$	$B_{33}$	$B_{12}$	$B_{13}$	$B_{23}$
O(2)	0.0009(1)	0.0158(22)	0.0273(28)	0.0004(9)	0.0029(10)	0.0249(43)
O(1)	0.0020(2)	0.0227(26)	0.0352(36)	0.0054(11)	0.0066(15)	0.0380(55)
C(1)	0.0009(2)	0.0160(31)	0.0133(27)	0.0019(4)	-0.0018(11)	0.0035(5)
C(2)	0.0008(1)	0.0052(0)	0.0107(22)	0.0000(7)	0.0001(1)	-0.0034(5)
C(3)	0.0009(2)	0.0175(27)	0.0126(38)	0.0007(1)	-0.0015(2)	-0.0035(8)
C(4)	0.0008(2)	0.0198(31)	0.0295(32)	-0.0024(13)	-0.0001(13)	-0.0121(37)
C(5)	0.0011(2)	0.0178(38)	0.0402(48)	-0.0041(14)	0.0036(18)	-0.0063(8)
C(6)	0.0008(2)	0.0332(36)	0.0279(43)	0.0014(14)	0.0045(16)	0.0102(7)
C(7)	0.0012(2)	0.0193(36)	0.0272(43)	0.0039(19)	0.0015(15)	0.0039(10)
C(8)	0.0015(2)	0.0126(28)	0.0172(33)	0.0015(1)	-0.0010(1)	0.0079(6)
C(9)	0.0014(2)	0.0070(22)	0.0174(29)	0.0001(13)	-0.0024(9)	-0.0037(6)
N(1)	0.0009(1)	0.0137(20)	0.0120(23)	0.0013(9)	-0.0009(1)	0.0079(38)
Br	0.0015(1)	0.0153(3)	0.0197(4)	0.0022(1)	-0.0016(2)	-0.0101(8)

The thermal parameters are of the form:

$$\exp(-B_{11}h^2 + B_{22}k^2 + B_{33}l^2 + B_{12}hk + B_{13}hl + B_{23}kl)$$

Table 1(c). *Positions (deduced) for the hydrogen atoms. Isotropic temperature factor of  $B = 2 \text{ \AA}^2$  was assumed for all hydrogens*

Atom	Bonded to	<i>x</i>	<i>y</i>	<i>z</i>
H(1)	N(1)	0.190	0.166	0.400
H(2)	N(1)	0.215	0.200	0.133
H(3)	N(1)	0.225	0.366	0.300
H(4)	O(1)	0.170	0.733	0.100
H(31)	C(3)	0.088	0.433	0.100
H(32)	C(3)	0.120	0.250	0.029
H(41)	C(4)	0.120	0.033	0.267
H(42)	C(4)	0.066	0.033	0.150
H(51)	C(5)	0.086	0.150	0.590
H(52)	C(5)	0.033	0.050	0.467
H(61)	C(6)	-0.013	0.320	0.550
H(62)	C(6)	0.025	0.375	0.333
H(71)	C(7)	0.060	0.450	0.733
H(72)	C(7)	0.015	0.583	0.600
H(81)	C(8)	0.100	0.700	0.600
H(82)	C(8)	0.083	0.640	0.317
H(91)	C(9)	0.133	0.400	0.567
H(92)	C(9)	0.167	0.575	0.533

#### Discussion of the structure

(a) *Bond lengths.* The bond lengths and bond angles in the molecule are given in Table 2 and also in Fig. 4. The average C—C bond length in the ring is 1.549 Å and is in good agreement with the mean value of 1.543 Å assigned by Bixon & Lifson (1967) from theoretical studies on the conformation of the cyclooctane ring. The corresponding value found in *cis*-cyclooctane-1,2-dicarboxylic acid (Burgi & Dunitz, 1968) is 1.530 Å, in *trans*-cyclooctane-1,2-dicarboxylic acid, 1.531 Å (Dobler *et al.*, 1966), and in spiro-3,6-dicyclooctylidene-1,2,4,5-tetraoxacyclohexane (Groth, 1967), 1.531 Å.

Table 2. *Bond lengths and bond angles observed in the molecule; esd are given in parentheses*

Bond	Length (Å)	Bond	Angle (deg)
C(1)—O(1)	1.339(17)	O(1)—C(1)—O(2)	123.7(1.1)
C(1)—O(2)	1.205(15)	O(1)—C(1)—C(2)	113.0(1.3)
C(1)—C(2)	1.513(16)	O(2)—C(1)—C(2)	123.3(1.3)
C(2)—C(3)	1.540(17)	C(1)—C(2)—C(3)	109.3(1.1)
C(3)—C(4)	1.560(19)	C(2)—C(3)—C(4)	119.4(1.2)
C(4)—C(5)	1.503(21)	C(3)—C(4)—C(5)	117.6(1.4)
C(5)—C(6)	1.579(22)	C(4)—C(5)—C(6)	116.8(1.5)
C(6)—C(7)	1.458(22)	C(5)—C(6)—C(7)	116.8(1.5)
C(7)—C(8)	1.597(21)	C(6)—C(7)—C(8)	122.1(1.6)
C(8)—C(9)	1.592(19)	C(7)—C(8)—C(9)	113.0(1.4)
C(9)—C(2)	1.564(16)	C(8)—C(9)—C(2)	115.5(1.3)
C(2)—N(1)	1.542(14)	C(9)—C(2)—C(3)	115.7(1.1)
		C(9)—C(2)—N(1)	108.1(1.1)
		N(1)—C(2)—C(1)	104.9(1.1)

(These compounds are abbreviated hereafter as the *cis* compound, the *trans* compound and the dimeric compound, respectively.) The average value of C—C distance in *n*-alkanes is  $1.533 \pm 0.002 \text{ \AA}$  (Bartell & Kohl, 1963). The only bond that appears rather short is C(6)—C(7), which is  $1.458 \text{ \AA}$ .

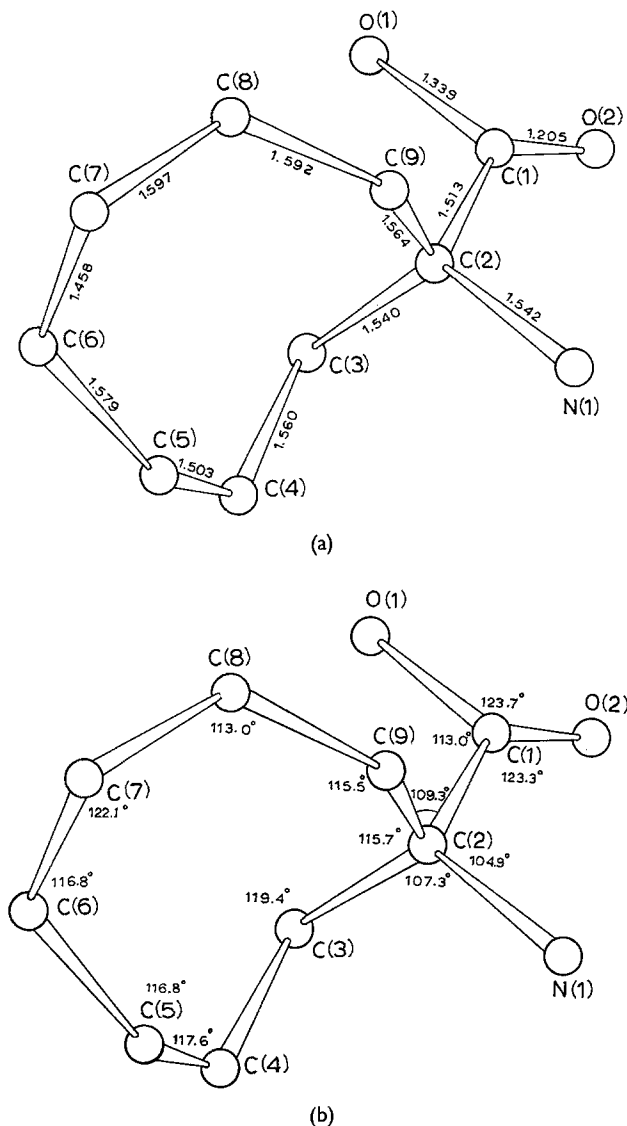


Fig. 4(a). Observed bond lengths. (b). Observed bond angles.

This is just outside the  $3\sigma$  level and it is not possible to say conclusively that it is significantly short. The C(7)—C(8) distance is  $1.597 \text{ \AA}$  and the C(8)—C(9) is  $1.593 \text{ \AA}$ . Although these are slightly larger than the average, they are within the  $3\sigma$  level.

The amino group is protonated and exists as  $\text{N}^+\text{H}_3$ . The C—N distance is  $1.542 \text{ \AA}$ . It is interesting to note that this is larger than the average C—N distance found in amino acids, which is  $1.487 \text{ \AA}$  (Marsh & Donohue, 1967). The larger values of C—N distance have been observed also in other



cycloalkane derivatives examined in this laboratory. For example in 1-aminocyclohexane hydrochloride, the C—N distance is 1.527 Å, in 1-aminocycloheptane hydrobromide monohydrate it is 1.544 Å (Chacko *et al.*, 1970) and in 1-aminocyclopentane hydrobromide it is 1.51 Å (Chandrasekharan *et al.*, 1968).

(b) *The carboxyl group.* This exists as —CO<sub>2</sub>H. The C=O and the C—O distances are 1.204 and 1.339 Å, respectively. The corresponding values in the *cis* compound are 1.225 and 1.305 Å and in the *trans* compound are 1.230 and 1.30 Å. A similar feature is observed in 1-aminocycloheptane hydrobromide and in 1-aminocyclohexane hydrochloride where the carboxyl group is not ionized (Chacko *et al.*, 1970).

(c) *Bond angles.* The bond angles in this structure are given in Table 2 and Fig. 4. The average C—C—C bond angle in the ring is 117.1° while the corresponding values in the *cis*, *trans* and dimeric compounds are 116.8°, 116.0° and 116.5°, respectively. The theoretical value predicted by Bixon and Lifson is 115°. The bond angles actually vary from 113 to 122°. Similar variations were also found in the related compounds. In the *cis* compound they vary from 114 to 120°; in the *trans* compound from 113 to 118° and in the dimeric compound from 115 to 119°, respectively. These variations, however, are within the 3 σ level of the bond angle errors and may not therefore be considered as significant.

(d) *Bond lengths and angles involving covalently bonded hydrogen.* As was mentioned earlier, the hydrogen atoms had been deduced from a difference Fourier at *R* = 11.9%. The bond distances X—H and angles X<sub>1</sub>—X<sub>2</sub>—H are given in Table 3. The mean C—H and N—H distances are 1.02

Table 3. *Intramolecular hydrogen bond distances and angles*

Bond	Distance (Å)	(C—X—H)	Angle (deg.)	(H—X—H)	Angle (deg.)
N(1)—H(1)	0.97	C(2)—N(1)—H(1)	87	H(1)—N(1)—H(2)	97
N(1)—H(2)	1.06	C(2)—N(1)—H(2)	112	H(2)—N(1)—H(3)	121
N(1)—H(3)	1.04	C(2)—N(1)—H(3)	108	H(1)—N(1)—H(3)	124
C(3)—H(31)	1.19	C(2)—C(3)—H(31)	93	H(32)—C(3)—H(31)	98
C(3)—H(32)	1.09	C(2)—C(3)—H(32)	112	H(42)—C(4)—H(41)	98
C(4)—H(41)	1.03	C(4)—C(3)—H(31)	123	H(52)—C(5)—N(51)	117
C(4)—H(42)	1.03	C(4)—C(3)—H(32)	107	H(62)—C(6)—H(61)	116
C(5)—H(51)	1.04	C(3)—C(4)—H(41)	99	H(72)—C(7)—H(71)	111
C(5)—H(52)	0.98	C(3)—C(4)—H(42)	112	H(82)—C(8)—H(81)	129
C(6)—H(61)	1.06	C(5)—C(4)—H(41)	115	H(92)—C(9)—H(91)	111
C(6)—H(62)	0.93	C(5)—C(4)—H(42)	111		
C(7)—H(71)	1.06	C(4)—C(5)—H(51)	107		
C(7)—H(72)	1.02	C(4)—C(5)—H(52)	103		
C(8)—H(81)	0.99	C(6)—C(5)—H(51)	110		
C(8)—H(82)	1.04	C(6)—C(5)—H(52)	100		
C(9)—H(91)	0.93	C(5)—C(6)—H(61)	119		
C(9)—H(92)	0.91	C(5)—C(6)—H(62)	102		
O(1)—H(4)	1.12	C(7)—C(6)—H(61)	102		
<i>Mean</i>		C(7)—C(6)—H(62)	97		
C—H	1.02	C(6)—C(7)—H(71)	105		
N—H	1.03	C(6)—C(7)—H(72)	103		
		C(8)—C(7)—H(71)	103		
		C(8)—C(7)—H(72)	110		
		C(7)—C(8)—H(81)	99		
		C(7)—C(8)—H(82)	107		
		C(9)—C(8)—H(81)	101		
		C(9)—C(8)—H(82)	105		
		C(8)—C(9)—H(91)	108		
		C(8)—C(9)—H(92)	121		
		C(1)—C(9)—H(91)	95		
		C(1)—C(9)—H(92)	100		

and 1.03 Å, respectively. Since no refinement of the hydrogen positions were attempted, a detailed discussion of these bond lengths and angles is not worthwhile.

Table 4. Deviations of the atoms from the respective least-squares planes for the cyclooctane ring and carboxyl group

Cyclooctane ring		Carboxyl group	
Atom	Deviation (Å)	Atom	Deviation (Å)
C(2)	0.11	C(2)	0.00
C(3)	-0.44	C(1)	-0.01
C(4)	-0.93	O(1)	0.00
C(5)	0.14	O(2)	0.01
C(6)	-0.59	N(1)	-0.07
C(7)	0.00		
C(8)	0.01		
C(9)	0.90		

(e) *Other intramolecular features.* The cyclooctane ring is puckered. It is possible to define a mean plane for the atoms in the ring and the maximum deviation of the atoms from this plane is  $\pm 0.9$  Å. The equation of the plane is given by

$$0.5592X - 0.2048Y + 0.8034Z = 2.8092$$

where  $X$ ,  $Y$  and  $Z$  are given in Å. The deviations of the atoms from this plane are given in Table 4. They are in fair agreement with the values given for this conformation by Bixon & Lifson (1967).

The carboxyl group is planar. The equation to the plane of the carboxyl group is

$$0.2990X + 0.5639Y + 0.7698Z = 3.9665$$

The amino nitrogen is almost in the plane of the carboxyl group, its deviation being only 0.007 Å. This feature is also observed in 1-aminocyclopentane hydrochloride, where the deviation of nitrogen is 0.01 Å from the plane of the carboxyl group (Chandrasekharan *et al.*, 1968). The deviations of the atoms from the least-squares plane are given in Table 4.

Table 5. Observed torsional angles of rotation around the C—C bonds in the cyclooctane ring, and the theoretical values of Bixon & Lifson (1967)

Angle	Observed (deg.)	Standard deviation* (deg.)	Theoretical (deg.)
C(1)—C(2)—C(3)—C(4)	296.5	1.4	296
C(2)—C(3)—C(4)—C(5)	67.2	1.6	64
C(3)—C(4)—C(5)—C(6)	40.5	1.8	46
C(4)—C(5)—C(6)—C(7)	261.9	1.6	255
C(5)—C(6)—C(7)—C(8)	67.2	1.9	70
C(6)—C(7)—C(8)—C(9)	294.6	1.8	288
C(7)—C(8)—C(9)—C(1)	97.9	1.3	106
C(8)—C(9)—C(1)—C(2)	313.6	1.4	316

\* This was calculated using the expression given by Huber-Buser & Dunitz (1961).

(f) *Torsion angles of rotation around the C—C bond in the octane ring.* The torsion angles of rotation around the C—C bond in the cyclooctane ring is given in Table 5, together with their standard deviations calculated using the expression given by Huber-Buser & Dunitz (1961). These are in good agreement with those in the *cis*, *trans* and dimeric compounds, in which the cyclooctane ring is in the same conformation. The cyclooctane ring in all these compounds exists in the *boat-chair* con-

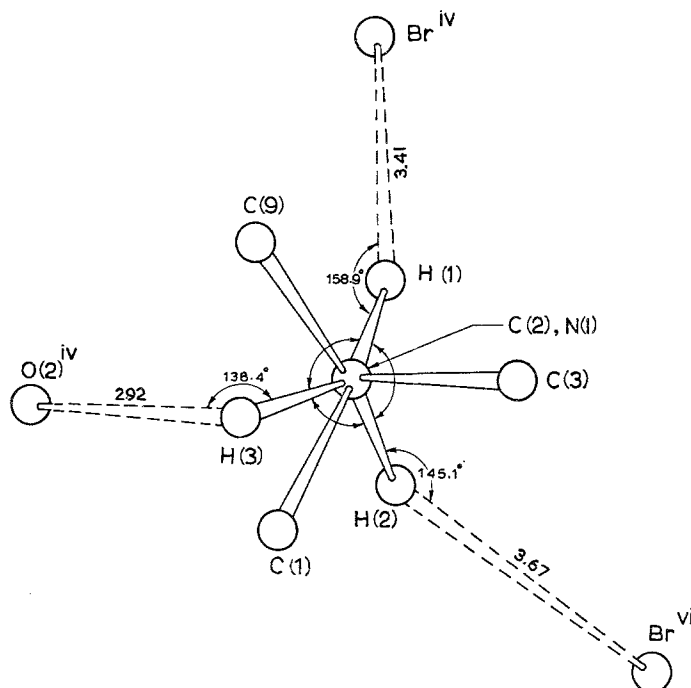


Fig. 5. Environment of N(1).

formation. The theoretical values of Bixon & Lifson (1967) are in good agreement with the experimental values and these are also given in Table 5.

(g) *Hydrogen bonding and molecular packing.* The crystal structure is stabilised by a three-dimensional network of hydrogen bonds. There are four hydrogen atoms in the molecule which may be expected to take part in intermolecular hydrogen bonding. Three hydrogen bonds from the amino

Table 6. *Hydrogen bond distances and angles*

Donor	Acceptor	N...A	H...A	C—N...A	N—H...A	H—N...A
C(2)—N(1)—H(1)...	Br <sup>iv</sup>	3.67 Å	2.75 Å	115.0°	158.9°	15.2°
C(2)—N(1)—H(2)...	Br <sup>vi</sup>	3.41	2.48	98.7	145.1	25.3
C(2)—N(1)—H(3)...	O(2) <sup>iv</sup>	2.93	2.07	103.4	138.4	27.9
C(1)—O(1)—H(4)...	Br <sup>i</sup>	3.15	2.21	159.1	148.4	31.8

Symmetry code:

- |  |   |
|--|---|
| (i) $x, y, z$                                    | (v) $\frac{1}{2} - x, 1 + \bar{y}, \frac{1}{2} + z$ |
| (ii) $x, 1 + y, z$                               | (vi) $\frac{1}{2} - x, \bar{y}, z - \frac{1}{2}$    |
| (iii) $x, y, 1 + z$                              | (vii) $\bar{x}, \frac{1}{2} + y, \frac{1}{2} - z$   |
| (iv) $\frac{1}{2} - x, \bar{y}, \frac{1}{2} + z$ | (viii) $1 + x, y, z$                                |

nitrogen N(1) are to two bromine atoms and one oxygen atom, with distances  $N(1)-H \cdots Br^{iv} = 3.41$  Å,  $N(1)-H \cdots Br^{vi} = 3.67$  Å and  $N(1)-H \cdots O(2)^{iv} = 2.92$  Å. The  $H-N(1) \cdots X$  angles with  $X = Br^{iv}$ ,  $Br^{vi}$  and  $O(2)^{iv}$  are 15, 25 and 27°, respectively. The hydrogen atoms attached to N(1) take up a staggered conformation with respect to C(1), C(3) and C(9), as may be seen from Fig. 5. The hydrogen

Table 7. Intermolecular non-bonded distances less than 4 Å

Atom	Atom	Distance (Å)	Atom	Atom	Distance (Å)
O(1) <sup>i</sup>	C(4) <sup>ii</sup>	3.74	Br <sup>i</sup>	C(3) <sup>iv</sup>	3.74
C(8) <sup>i</sup>	C(4) <sup>ii</sup>	3.84	N(1) <sup>i</sup>	C(1) <sup>iv</sup>	3.96
C(8) <sup>i</sup>	C(5) <sup>ii</sup>	3.91	O(2) <sup>i</sup>	O(2) <sup>iv</sup>	3.43
C(7) <sup>i</sup>	O(1) <sup>iii</sup>	3.99	Br <sup>i</sup>	O(2) <sup>v</sup>	3.81
C(8) <sup>i</sup>	O(1) <sup>iii</sup>	3.69	Br <sup>i</sup>	C(1) <sup>v</sup>	3.91
C(9) <sup>i</sup>	O(1) <sup>iii</sup>	3.68	O(2) <sup>i</sup>	C(2) <sup>vi</sup>	3.62
C(9) <sup>i</sup>	O(2) <sup>iii</sup>	3.97	O(2) <sup>i</sup>	C(9) <sup>vi</sup>	3.49
C(9) <sup>i</sup>	C(1) <sup>iii</sup>	3.91	O(2) <sup>i</sup>	C(1) <sup>vi</sup>	3.76
O(2) <sup>i</sup>	O(2) <sup>v</sup>	3.43	C(4) <sup>i</sup>	C(6) <sup>vii</sup>	3.82

The numbers given in brackets refer to the symmetry code (see Table 6).

atom attached to O(1) is hydrogen bonded with Br, the  $O-H \cdots Br$  distance being 3.15 Å. The hydrogen bond distances and angles are given in Table 6 and the non-bonded distances less than 4 Å are given in Table 7; there are no unusually short contacts. A view of the structure projected down the *c* axis is shown in Fig. 6.

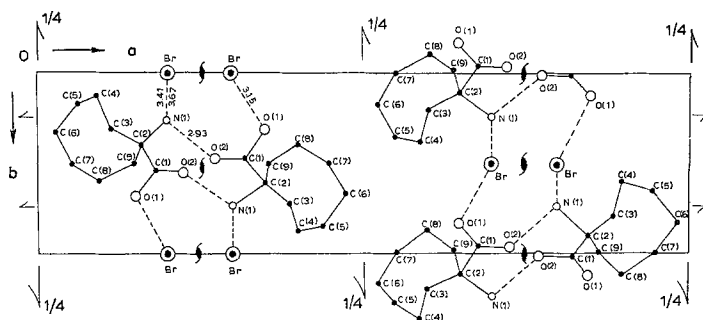


Fig. 6. Structure viewed down the *c* axis. Hydrogen bonds are shown by dashed lines.

### Conformational features

(a) *Carboxyl group*. The conformational features of the amino acids, as already mentioned in the introduction, have been studied extensively in our laboratory. The notation followed is that of Edsall *et al.* (1966). The angles  $\psi_1$  and  $\psi_2$  describe the disposition of the two C—O bonds of the carboxyl group and measure the clockwise notation of the two C—O bonds about the C—C' bond with respect to the C—N bond. The two angles are usually found to be around 0 and 180°, respectively. In this structure, the values are 355 and 178.3°, respectively.

(b) *Cyclooctane ring*. The possible conformations which the cyclooctane ring can take up have been predicted theoretically by a number of workers (Allinger, 1959, 1968; Hendrickson, 1961, 1963, 1964; Wiberg, 1965; Pauncz & Ginsberg, 1960; Bixon & Lifson, 1967). The expected bond lengths,

bond angles, the torsion angles around the C—C bond in the ring and the deviations of the atoms in the cyclooctane ring from the mean least-squares plane for all the conformations have also been given.

The cyclooctane ring in this structure exists in the *boat-chair* conformation of Hendrickson (1964), which is also conformation I of Bixon & Lifson (1967). The predicted torsion angles for this conformation agree well with the observed values (Table 5). This conformation of the cyclooctane ring is also found in the *cis*, *trans* and the dimeric compounds. A detailed comparative study of the conformational features of common ring systems are under investigation and will be reported independently.

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