

Charge Density in the Crystal Structure of γ -Aminobutyric Acid at 122 K – An Intramolecular Methylene H Bridge

BY B. M. CRAVEN

Department of Crystallography, University of Pittsburgh, Pittsburgh, PA 15260, USA

AND H.-P. WEBER

Mineralogisches-Petrographisches Institut, Universität Kiel, Olshausenstrasse 40-60, D-2300 Kiel, Federal Republic of Germany

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Abstract

The charge density in γ -aminobutyric acid (GABA) at 122 K has been determined from X-ray (Mo $K\alpha$) intensity data (3394 reflections with $F_o > 4\sigma$ and $\sin \theta/\lambda \leq 1.3 \text{ \AA}^{-1}$). Least-squares refinements were carried out using Stewart's rigid pseudoatom model. Fixed neutron values were used for positional parameters and H-atom U_{ij} parameters. The sum of net atomic charges is $-0.6 e$ for the carboxylate group and $+0.6 e$ for the ammonium H atoms. The calculated molecular dipole moment is 13 (1) debye (1 debye = $3.336 \times 10^{-30} \text{ C m}$). Unexpectedly, there is a methylene H atom carrying a positive charge of $+0.11 (2) e$ which forms an intramolecular bridge between negatively charged N and O atoms, $-0.23 (3)$ and $-0.15 (2) e$, respectively. This interaction may help to stabilize the folded conformation of the zwitterion. [Crystal data: $\text{C}_4\text{H}_9\text{NO}_2$, $P2_1/a$, $a = 8.217 (3)$, $b = 10.005 (11)$, $c = 7.210 (4) \text{ \AA}$, $\beta = 110.60 (4)^\circ$.]

Introduction

The zwitterion γ -aminobutyric acid (GABA) is of interest because it is believed to be a neurotransmitter in the mammalian central nervous system (Davidson, 1976).

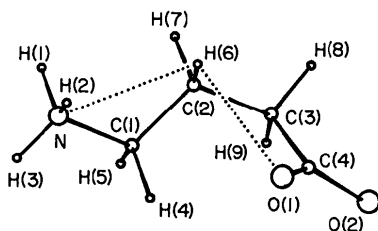


Fig. 1. Atomic nomenclature for GABA with the molecule in the observed conformation. Dotted lines represent the $\text{N}\cdots\text{H}\cdots\text{O}$ intramolecular bridge interaction.

The X-ray crystal structure of GABA was first determined by Steward, Player & Warner (1973). They found the molecule to be a zwitterion with a folded conformation (Fig. 1). We have previously determined the crystal structure of GABA at 122 K by neutron diffraction so as to provide further details of the nuclear arrangement including the H atoms (Weber, Craven & McMullan, 1983; hereafter WCM). We now report an X-ray structure determination of the electronic charge density distribution.

Experimental

The crystal structure of GABA is monoclinic with space group $P2_1/a$ and four molecules per unit cell. The two crystals of GABA which were used for X-ray data collection were grown from aqueous solution. They exhibited the forms $\{001\}$, $\{110\}$ and were both about 0.5 mm along c , with crystal volumes of 0.014 and 0.114 mm^3 respectively.

The data were measured using an Enraf–Nonius CAD-4 diffractometer with Mo $K\alpha$ radiation ($\lambda = 0.7093 \text{ \AA}$) obtained by 002 reflection from a graphite monochromator. The crystal, which was mounted with c^* close to the diffractometer ϕ axis, was cooled in a stream of nitrogen gas provided by an Enraf–Nonius device. The temperature (122 K) was monitored ($\pm 2 \text{ K}$) using a thermocouple in the cold stream, 8 mm upstream from the crystal.

The crystal-lattice parameters for GABA were obtained by least-squares fit of $\sin^2 \theta$ values which were measured at $\pm \omega$ for 25 reflections in the range $20 < \theta < 33^\circ$. These parameters (see *Abstract*), are in good agreement with the neutron values (Table 1 in WCM) which were also obtained at 122 K. The X-ray lattice parameters were used in the present structure refinements.

The integrated X-ray intensities were measured by $\omega/2\theta$ scans with scan width given by $\Delta(2\theta) = (2.2 + 0.7 \tan \theta)^\circ$. An equal time was spent on scanning and on the background, which was measured at each scan limit. There were insignificant changes in the intensities of four monitor reflections which were measured after every 75 reflections. The first crystal was lost after measuring 3320 reflections, which were mostly those with $0 \leq l \leq 6$ and $\sin \theta/\lambda \leq 1.08 \text{ \AA}^{-1}$. The larger crystal was used for measuring another 3797 reflections extending to $\sin \theta/\lambda = 1.30 \text{ \AA}^{-1}$. In the range $\sin \theta/\lambda > 1.08 \text{ \AA}^{-1}$, only those reflections were measured having normalized structure amplitudes with values $|E_{hkl}| \geq 1.5$, in calculations based on the WCM neutron structure parameters. The intensities were corrected for X-ray absorption ($\mu = 0.103 \text{ mm}^{-1}$) using a numerical integration procedure (Busing & Levy, 1957). The range of transmission factors was 0.91 to 0.96. Only those reflections with structure amplitudes $|F_o| > 4\sigma(F)$ were included in subsequent calculations. In applying this criterion, it was assumed that $\sigma^2(I) = \sigma^2 + (0.02I)^2$ where σ^2 is the variance in an integrated intensity (I) due to counting statistics. There remained 1885 reflections from the first crystal and 1900 from the second. These were scaled together by a least-squares procedure (Hamilton, Rollett & Sparks, 1965) to give a total of 3394 non-symmetry-related reflections. The R factor was 0.052 for the 231 reflections, mostly weak, which were common to both sets of data.

When the integrated intensity of the moderately strong 002 reflection was measured at 10° intervals of crystal rotation about c^* , there were sinusoidal variations with an amplitude of 14% of the maximum value, and period of 180° . These variations were about three times greater than the calculated effect of X-ray absorption with change of crystal path length. Thus it was suspected that the 002 reflection and perhaps others were affected by secondary extinction. However, in the subsequent structure refinement the effect of extinction was neglected when it was found that the isotropic-extinction parameter had a value insignificantly different from zero.

Structure refinements

The electronic charge density in GABA has been determined by least-squares refinements (Craven & Weber, 1981) using aspherical pseudoatom scattering factors, as proposed by Stewart (1976). Details of the expressions used in the refinement model have been given by Epstein, Ruble & Craven (1982) in an Appendix. The static charge density about each atom center was taken as the sum of an invariant core component and a set of charge deformation terms, each with a variable population parameter. For the C, N and

O pseudoatoms in GABA, the core was assumed to be a neutral spherical Hartree-Fock atom with the scattering factor given by Cromer & Waber (1974). For H, the core was a neutral spherically approximated bonded atom (Stewart, Davidson & Simpson, 1965). Each charge deformation term was taken as the product of a single Slater-type radial function and a multipole angular function. The radial exponent parameter was assigned a fixed value, $\alpha = 3.2, 3.9, 4.5$ or 2.4 bohr^{-1} (the Bohr radius is 52.92 pm) for C, N, O and H atoms respectively, these values being chosen on the basis of our experiences in similar structure determinations (Craven & McMullan, 1979; Craven, Fox & Weber, 1982). The radial functions then become appropriate for describing charge deformations only in the outer or valence shell of each pseudoatom. A complete set of multipole angular terms was used, extending to octapole (quadrupole for H atoms).

In the refinement, fixed neutron values (from WCM) were used for all nuclear positional parameters and for H-atom anisotropic thermal parameters. The total of 238 least-squares variables consisted of a scale factor, the anisotropic thermal parameters for non-H atoms, and the 193 electron population parameters. Full-matrix least-squares refinement was carried out in order to minimize $\sum w\Delta^2$ where $\Delta = |F_o| - |F_c|$ and $w = \sigma^{-2}(F_o)$. Convergence was obtained with the monopole population parameters giving $-\sum p_v = 0.69 (19) e$. This value, which is the net charge on the molecule, was considered to be satisfactorily close to the required value of zero. In subsequent refinement, the net charge was constrained to be zero, thus giving rise to a small increase (4σ) in the scale factor.

A final difference Fourier synthesis showed several significant features in the residual density, indicating that there were deficiencies in the assumed structure model. Of particular concern were the peak of $0.60 (6)$ and trough of $-0.50 (6) e \text{ \AA}^{-3}$ near atom O(1), shown in Fig. 2(a). When positional parameters were included as new least-squares variables, atom O(1) moved $0.023 (2) \text{ \AA}$ towards the positive peak in Fig. 2(a). The residual features near O(1) were reduced in magnitude to $\pm 0.36 (6) e \text{ \AA}^{-3}$, but are still significant (Fig. 2b). Further improvement was obtained by returning to the fixed neutron positional parameters and allowing for anharmonic thermal motion by introducing third-order thermal parameters, c_{jkl} [see equation (5.2.3.9) in Johnson & Levy (1974)]. From analysis of the neutron U_{ij} values for GABA, WCM concluded that the carboxylate group librates harmonically about the C(4)-C(3) bond with m.s. amplitude $25 (5) \text{ deg}^2$. However, on one side of the carboxylate plane (Fig. 1), there is an intramolecular distance O(1)···H(6) which is short (2.54 \AA) compared with the sum of the van der Waals radii (2.6 \AA ; Pauling, 1960), whereas on the other side the shortest such distance O(1)···H(4) is 2.62 \AA . Thus, anharmonic librational motion might be

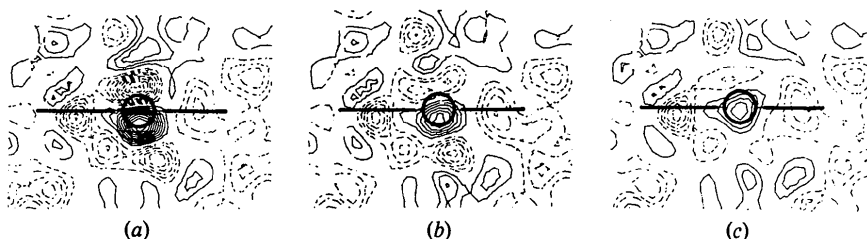


Fig. 2. Residual electron density showing effects of anharmonic librational motion in the section through O(1) normal to the C(4)—O(1) bond. The lines are the trace of the carboxylate plane, ending at the projected positions of O(2) on the right and C(3) on the left. Atoms H(6) and H(4) (not shown) are above (0.4 Å) and below (2.0 Å) these lines and to the left of O(1). Contours at 0.05 e Å⁻³ with zero omitted. (a) Refinement with neutron positional parameters. (b) Refinement with X-ray positional parameters. (c) Refinement with neutron positional parameters, including third-order temperature factors.

expected with greater probability of finding O(1) on the side of the carboxylate plane opposite from H(6). This is consistent with the observed residual density (Fig. 2a). Because of computer limitations, full-matrix least-squares refinement with the addition of 70 c_{jkl} variables could not be carried out. Variables were grouped in two large blocks such that all correlation factors were less than 0.5 for variables in different blocks. The first block consisted of 138 monopole and quadrupole population parameters and the non-H-atom anisotropic thermal parameters. The second consisted of 167 dipole and octapole population parameters and the 70 third-order thermal parameters. The largest

correlation factors within each block were 0.8 between three pairs of U_{ij} and q_j parameters for the same O atom, and 0.6 between 17 pairs of c_{jkl} parameters in which members of each pair belong to the same non-H atom. Convergence was obtained with $R_w = 0.038$, $R = 0.049$, $QME = 1.41$. For atom O(1), seven c_{jkl} values were significantly non-zero, in contrast to the total of five for all other non-H atoms (Table 1). The residual charge density near atom O(1) was reduced to 0.25 (6) e Å⁻³ at the atom center (Fig. 2c). Difference Fourier syntheses were also calculated in the sections through the molecular backbone at the amino and carboxylate ends and at distances ±0.4 Å from these planes.* The most significant feature was the trough of -0.36 (5) e Å⁻³ between atoms O(1) and H(6) which is seen near its maximum value in Fig. 2(c).

The parameter values from this refinement, which are given in Tables 1 and 2,* form the basis of further discussion. According to the R -factor-ratio test (Hamilton, 1974), the structure model which includes third-order temperature factors is an improvement which can be accepted with more than 99.5% confidence over

Table 1. X-ray atomic thermal parameters for GABA at 122 K

(a) Anisotropic thermal parameters, U_{ij} (Å² × 10⁴)

The temperature-factor expression is

$$T = \exp(-2\pi^2 \sum_i \sum_j h_i h_j a_i^* a_j^* U_{ij}).$$

	U_{11}	U_{22}	U_{33}	U_{12}	U_{13}	U_{23}
N	140 (3)	221 (3)	126 (1)	-1 (3)	43 (1)	-22 (2)
C(1)	182 (3)	169 (3)	139 (2)	-32 (3)	45 (2)	6 (2)
C(2)	191 (3)	188 (3)	117 (1)	-48 (3)	44 (2)	0 (2)
C(3)	146 (3)	284 (4)	118 (2)	2 (3)	41 (2)	1 (2)
C(4)	152 (2)	203 (3)	112 (1)	48 (2)	42 (1)	2 (2)
O(1)	271 (4)	470 (6)	184 (2)	233 (4)	66 (2)	43 (3)
O(2)	179 (3)	356 (4)	137 (2)	69 (3)	69 (2)	50 (2)

* Tables of observed and calculated structure amplitudes and a residual density map have been deposited with the British Library Lending Division as Supplementary Publication No. SUP 38571 (39 pp.). Copies may be obtained through The Executive Secretary, International Union of Crystallography, 5 Abbey Square, Chester CH1 2HU, England.

Table 1 (cont.)

(b) Third-order thermal parameters, c_{jkl} (× 10⁷)

$$\text{The temperature-factor expression is } T = 1 - (4/3)\pi^3 i \sum_j \sum_k \sum_l h_j h_k h_l c_{jkl}.$$

	c_{111}	c_{222}	c_{333}	c_{112}	c_{122}	c_{113}	c_{133}	c_{223}	c_{233}	c_{123}
N	0 (2)	3 (2)	2 (2)	-1 (1)	-1 (1)	-1 (1)	-1 (1)	-2 (1)	-3 (1)	0 (1)
C(1)	3 (3)	1 (2)	-5 (2)	-1 (2)	-1 (1)	4 (2)	6 (1)	1 (1)	0 (1)	1 (1)
C(2)	-12 (3)	1 (2)	-3 (2)	1 (2)	2 (1)	-3 (2)	0 (1)	4 (1)	0 (1)	0 (1)
C(3)	3 (2)	0 (2)	-1 (2)	-5 (2)	-6 (1)	-2 (1)	-2 (1)	1 (1)	2 (1)	-2 (1)
C(4)	-2 (2)	0 (1)	-3 (2)	0 (1)	2 (1)	2 (1)	-1 (1)	-1 (1)	-2 (1)	-2 (1)
O(1)	25 (4)	20 (3)	-1 (2)	31 (3)	26 (3)	8 (2)	-2 (2)	8 (2)	-1 (2)	8 (2)
O(2)	-2 (3)	-13 (2)	-1 (2)	2 (2)	-6 (2)	-1 (2)	-1 (1)	-7 (1)	-3 (1)	-1 (1)

other models.* This includes the model in which non-H-atom positional parameters are determined from the X-ray structure amplitudes.

* Re-examination of the WCM neutron structure showed a residual neutron scattering density with features near O(1) very similar to those of Fig. 2(a), but at lower significance levels (3σ). When neutron least-squares refinements were carried out including c_{jkl} variables for all atoms, there was improvement in agreement which could be accepted at the 90% level of confidence (Hamilton, 1974). The most significantly non-zero c_{jkl} value was $c_{112} = 21(4) \times 10^7$ for atom O(1), in good agreement with the X-ray value (Table 1). However, because of the limited extent of the data ($\sin \theta/\lambda < 0.78 \text{ \AA}^{-1}$), these neutron results are considered as confirmative rather than conclusive with respect to the anharmonic thermal motion of O(1).

Table 2. *Electron population parameters for GABA at 122 K*

These values (electrons $\times 10^2$) are for charge density terms as defined in an Appendix by Epstein, Ruble & Craven (1982). Radial charge density functions are of Slater-type with fixed exponent parameters, $\alpha = 3.2, 3.9, 4.5$ and 2.4 bohr^{-1} for C, N, O and H atoms respectively. Multipole functions are referred to local Cartesian axes for each pseudoatom which have directions $\mathbf{x} = \mathbf{u}$, $\mathbf{z} = \mathbf{u} \times \mathbf{v}$, $\mathbf{y} = \mathbf{z} \times \mathbf{u}$ where \mathbf{u} and \mathbf{v} are the intramolecular vectors given below.

	\mathbf{u}	\mathbf{v}		\mathbf{u}	\mathbf{v}
N	H(1) to H(2)	C(1) to H(3)	H(1)	N to H(1)	H(2) to H(3)
C(1)	H(4) to H(5)	C(2) to N	H(2)	N to H(2)	H(3) to H(1)
C(2)	H(7) to H(6)	C(3) to C(1)	H(3)	N to H(3)	H(1) to H(2)
C(3)	H(9) to H(8)	C(4) to C(2)	H(4)	C(1) to H(4)	C(2) to N
C(4)	C(3) to C(4)	O(2) to O(1)	H(5)	C(1) to H(5)	C(2) to N
O(1)	C(4) to O(1)	O(2) to O(1)	H(6)	C(2) to H(6)	C(3) to C(1)
O(2)	C(4) to O(2)	O(2) to O(1)	H(7)	C(2) to H(7)	C(3) to C(1)
			H(8)	C(3) to H(8)	C(4) to C(2)
			H(9)	C(3) to H(9)	C(4) to C(2)

Note that for tetrahedrally bonded atoms, the Cartesian axes are the bisectors of bond angles. For other atoms, the x axis is along a bond. The monopole population parameters (p_i) are equal and opposite in sign to the pseudoatom net charges (Fig. 1). The higher multipole parameters are for dipole (d_i), quadrupole (q_i) and octapole (o_i) deformations.

For GABA at 122 K, the X-ray values for U_{11} and U_{22} (Table 1) are consistently smaller than the WCM neutron values. However, only four of all U_{ij} differences are significant, the largest being $\Delta U_{11} = 0.0018(4) \text{ \AA}^2$ for the N atom.

Discussion

(a) The net atomic charges

The net charge on each pseudoatom is the negative value of the corresponding monopole electron population parameter (Table 2). The magnitudes of these charges should be interpreted with caution because they depend on the nature of the assumed charge density radial function. However, there is significance in making comparisons of the charges on pseudoatoms of the same kind, since these have the same radial function. Thus, the three tetrahedral C atoms are neutral within experimental error, whereas the trigonal carboxylate C atom has a significant negative charge, $-0.17(3) \text{ e}$. This charge appears to be an inductive effect due to the carboxylate O atoms. The carboxylate O atoms differ in charge, as might be expected from their different intra- and intermolecular environment. The more electronegative atom O(2) has the longer C—O bond by at least 0.01 \AA ,* and is engaged in two N—H...O H bonds, while atom O(1) forms only one.

The most interesting comparison of charges involves the H atoms. The H atoms of the ammonium group are

* The WCM neutron bond lengths C—O(2) and C—O(1) are $1.271, 1.258 \text{ \AA}$ respectively, after correction for thermal motion.

Table 2 (cont.)

	p_v	d_1	d_2	d_3	q_1	q_2	q_3	q_4	q_5
N	23 (3)	0 (1)	1 (1)	-2 (1)	3 (2)	7 (2)	-6 (1)	12 (2)	-4 (2)
C(1)	-5 (4)	-3 (2)	-5 (2)	-2 (1)	4 (2)	-6 (2)	-7 (1)	-11 (2)	2 (2)
C(2)	4 (4)	3 (2)	1 (2)	-3 (2)	3 (2)	10 (2)	-10 (2)	4 (2)	-1 (2)
C(3)	-3 (4)	-1 (2)	-2 (2)	-2 (2)	8 (2)	1 (2)	3 (1)	1 (2)	10 (2)
C(4)	17 (3)	2 (2)	5 (2)	-2 (2)	-6 (1)	10 (1)	-1 (1)	-2 (1)	-22 (2)
O(1)	15 (2)	2 (1)	4 (2)	-12 (2)	3 (2)	-1 (2)	-2 (2)	-7 (2)	2 (2)
O(2)	27 (2)	6 (2)	-2 (2)	7 (2)	-14 (2)	-3 (2)	0 (1)	2 (2)	1 (2)
H(1)	-18 (2)	-15 (2)	0 (2)	2 (2)	6 (2)	-3 (2)	-5 (2)	-1 (2)	-3 (2)
H(2)	-19 (2)	-10 (2)	5 (2)	1 (2)	6 (2)	0 (2)	-5 (2)	-1 (2)	-5 (2)
H(3)	-20 (2)	-7 (2)	1 (2)	-5 (2)	5 (2)	-4 (2)	5 (2)	3 (2)	-10 (2)
H(4)	-1 (2)	-18 (2)	1 (2)	4 (2)	9 (2)	-2 (2)	4 (2)	2 (2)	-5 (2)
H(5)	-3 (2)	-13 (2)	0 (2)	1 (2)	7 (2)	5 (2)	-5 (2)	1 (2)	-3 (2)
H(6)	-11 (2)	-11 (2)	-2 (2)	-2 (2)	7 (2)	-1 (2)	-2 (2)	2 (2)	-5 (2)
H(7)	3 (2)	-16 (2)	2 (2)	3 (2)	9 (2)	-7 (2)	-1 (2)	-1 (2)	-4 (2)
H(8)	-4 (2)	-11 (2)	-4 (2)	2 (2)	6 (3)	4 (2)	-6 (2)	1 (2)	1 (2)
H(9)	-4 (2)	-12 (2)	2 (2)	-3 (2)	9 (2)	-6 (2)	3 (2)	1 (2)	-1 (2)
		o_1	o_2	o_3	o_4	o_5	o_6	o_7	
N		5 (2)	-1 (2)	-25 (2)	2 (2)	-3 (2)	-1 (2)	-1 (2)	
C(1)		0 (2)	-2 (2)	-32 (2)	-6 (2)	1 (2)	-2 (2)	-1 (2)	
C(2)		-1 (2)	1 (2)	-35 (2)	-2 (2)	5 (2)	3 (2)	3 (2)	
C(3)		3 (2)	-4 (2)	-32 (2)	-7 (2)	4 (2)	-4 (2)	-1 (2)	
C(4)		-33 (2)	-6 (2)	0 (2)	-1 (2)	4 (2)	-1 (2)	1 (2)	
O(1)		-3 (3)	-4 (3)	0 (2)	1 (3)	2 (2)	2 (3)	-2 (2)	
O(2)		-6 (2)	-1 (2)	2 (2)	-1 (2)	-3 (2)	5 (2)	-3 (2)	

electropositive with charges which are all the same within the experimental error (average value, $+0.19 e$). These H atoms are also similar in other respects. The N—H bond lengths are indistinguishable (1.08 \AA),* and the three N—H \cdots O H bonds are similar, with H \cdots O distances 1.71 , 1.74 and 1.69 \AA , and N—H \cdots O angles 168 , 163 and 171° . Except for atom H(6), the H atoms of the methylene chain are electrostatically neutral. Thus, in experimental charge density studies, the electropositivity of the H atoms is a general feature distinguishing those which are H bonded from those which are not. Results similar to those in GABA are found in other structures (Craven, Fox & Weber, 1982; Epstein, Ruble & Craven, 1982; Craven & Benci, 1981). However, atom H(6) in GABA has a significantly positive net charge with a value $0.11 (2) e$ which is intermediate between those of the other methylene H atoms, and the H-bonded H atoms of the ammonium group. From a study of the crystal environment of the methylene H atoms, it was found that only H(6) was within short intramolecular distance of the two electronegative N and O(1) atoms, the distances being 2.64 and 2.54 \AA (Fig. 1). The corresponding sums of the van der Waals radii are 2.7 and 2.6 \AA (Pauling, 1960). These short distances come from the folding of the molecular backbone into a twisted conformation, with torsion angle $\pm 72.6 (1)^\circ$ about the C(2)—C(3) bond. We propose that the positive charge at H(6) is induced as the molecule folds and that the resulting H bridge N \cdots H \cdots O $^-$ helps to stabilize the observed conformation. The interaction is described as H bridging because the distances and angles (C—H \cdots N, 69° ; C—H \cdots O, 91° ; N \cdots H \cdots O, 109°) are outside the limits for conventional H bonding (Jeffrey & Maluszynska, 1982). We have calculated the electrostatic potential energy for an isolated GABA molecule in the observed conformation, with atomic point charges having their experimental values. When the net charge on H(6) is set to zero, the configuration becomes less stable by 8.4 kJ mol^{-1} .

Similar intramolecular H bridging may affect the conformation in other molecules, such as the malonate ion. In the neutron structure of calcium malonate dihydrate (Albertsson, Oskarsson & Svensson, 1978), we note a methylene atom H(21) bridging two carboxylate O atoms. The O \cdots H \cdots O intramolecular distances are both short (2.49 , 2.52 \AA) and the angle is 113° . The C—H \cdots O angles are both 71° . In this case, no charge density study has been carried out. The methyl H atoms of the choline moiety may also form intramolecular N \cdots H \cdots O bridges and thus influence the conformation of acetylcholine and the lecithin head group. However, details are lacking for the H-atom positions in such molecules.

* This is a neutron value including an approximate thermal-motion correction, $\sim 0.04 \text{ \AA}$.

(b) Asphericity of the pseudoatoms

When local reference axes are appropriately chosen, atoms N, C(1), C(2) and C(3) have only one important octapole deformation term (o_3 in Table 2) which describes a tetrahedral arrangement of bonding charge density. The value of this term is in good agreement for all three tetrahedral C atoms. The static charge deformation density in the best least-squares plane through the ammonium end of the molecule is shown in Fig. 3.

Atom C(4) of the carboxylate group has a predominant octapole term o_1 which describes a trigonal arrangement of bonding density (Fig. 4a). Additionally, there is an important quadrupole term q_5 which enhances charge density in the carboxylate plane, while depleting charge from above and below it. These two

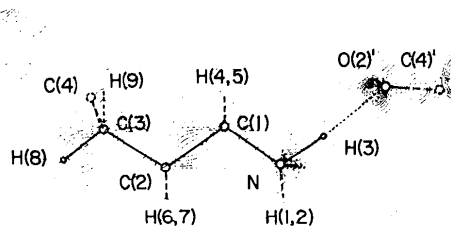


Fig. 3. The static charge deformation density including monopole terms, in the best least-squares plane through the ammonium end of the molecule. Dashed lines are bonds to atoms not in the plane and the dotted line represents the H bond. Contours are at intervals $0.1 e \text{ \AA}^{-3}$ with dashed contours in regions of deficient electron charge. Largest values ($e \text{ \AA}^{-3}$) are $1.00 (8)$ in the N—H bond, $0.81 (5)$ in C—H bonds, $0.62 (4)$ in C—C bonds.

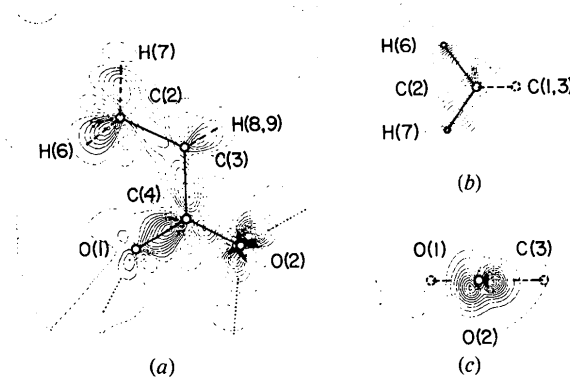


Fig. 4. Charge deformation maps, with contours as in Fig. 3. (a) The best least-squares plane through the carboxylate end of the molecule. The largest value for the charge deformation occurs in the C(4)—O(1) bond, $0.96 (16) e \text{ \AA}^{-3}$. (b) The plane through a methylene group. The other methylene groups give very similar maps. (c) Section through the O(2) atom center and normal to the C(4)—O(2) bond. The plane of the carboxylate group is represented by the trace of the C(4)—O(1) and C(4)—C(3) bonds. The largest deformation density in the zwitterion occurs in the lobes at O(2), $1.32 (13) e \text{ \AA}^{-3}$.

deformations are also characteristic of the charge density at the C atom of amide groups (Craven, Fox & Weber, 1982).

The deformation density at atom O(2) has an important quadrupole term q_1 , describing lobes which are directed normal to the C—O bond and are close to the carboxylate plane (Fig. 4c). Similar features are observed at the carboxylate O atoms in α -glycine (Almlöf, Kvik & Thomas, 1973). However, there are no such lobes at atom O(1) which is unusual in being almost spherically symmetric except for one strong dipole deformation term, d_3 (Table 2). Since this deformation is parallel and in the same sense as the antisymmetric residual features near O(1) in Fig. 2(a), it is possible that asphericity in the valence charge density near O(1) has been poorly deconvoluted from the thermal motion.

For all H atoms, the largest charge deformation is a dipole which is directed close to the C—H or N—H bond, and acts to enhance the charge in the covalent bonding region. The local dipole moment at each H atom (following Stewart, 1972) is 0.84, 0.61, 0.46 debye at the ammonium H atoms, and ranges from 0.64 to 1.04 (16) debye for the methylene H atoms. All have directions within 35° of the C—H or N—H bond vector.

(c) The molecular dipole moment

From the observed atomic charges as discussed in (a), it is concluded that the zwitterion is poorly represented by the conventional structure formula with a positive and negative unit charge at each end, particularly when the formal positive charge is shown on the N atom. Thus the positive charge of the ammonium group, which comes from the H atoms, +0.57 (3) e, is partly offset by the negatively charged N atom, -0.23 (3) e. The carboxylate group provides the most concentrated region of excess negative charge, -0.59 (4) e. From the observed net charges and atomic dipole terms, we have calculated (following Stewart, 1972) that the molecular dipole moment is 13 (1) debye.

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