The Crystal and Molecular Structure of *l*-Cocaine Hydrochloride

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The structure of the hydrochloride of *l*-cocaine (*l*-3-tropanylbenzoate-2-carboxylic acid methyl ester) has been determined from a three-dimensional Patterson synthesis, with the aid of the $0kl$ Patterson function for the hydrobromide and the $0kl$ electron-density map of the hydrochloride, and has been refined by three-dimensional Fourier methods. Crystals of both the hydrochloride and the hydrobromide are orthorhombic, space group $P2_12_12_1$: for the hydrochloride, $a=7\cdot633$, $b=10\cdot300$, $c=21\cdot459$ Å; for the hydrobromide, $a=7\cdot68$, $b=10\cdot68$, $c=21\cdot65$ Å. The stereochemical configuration found for the cocaine molecule agrees with that deduced from chemical evidence. The piperidine ring of the tropane nucleus has the chair form, with C(3) displaced less, and N displaced more, than usual from the plane of the ring. The benzoxy side-chain on C(3) is equatorial, and the carbomethoxy side-chain on C(2) is axial. The substituents are *cis* to each other and to the nitrogen atom.

Introduction

The narcotic *l*-cocaine occurs in the leaves of the coca bush, a member of the genus *Erythroxylon*, from which it was first isolated by Wöhler (1862). The chemical relationship of the molecule (Fig. 1(*a*)) with that of ecgonine (Fig. 1(*b*)) was soon realized and *l*-cocaine was prepared from *l*-ecgonine by Merck (1885). The principal features of the chemical constitution of *l*-ecgonine were deduced from oxidation and dehydration studies, primarily by Liebermann (1890), and the structural formulae of *l*-ecgonine and *l*-cocaine were finally established unambiguously on the basis of direct syntheses by Willstätter, Wolfes & Mäder (1923). A full review of the earlier work on the tropane alkaloids is given by Holmes (1950). The stereochemical configuration of *l*-ecgonine, and of *l*-cocaine, was elucidated with reasonable certainty between 1954 and 1956 (Fodor, 1960).

Cocaine has been classified as an arylpiperidine (Farmilo & Levi, 1953) in the same group of narcotics as alphaprodine and betaprodine, of which the crystal structures of the hydrochloride and hydrobromide, respectively, have been determined previously in this laboratory (Kartha, Ahmed & Barnes, 1960, 1961; Ahmed, Barnes & Masironi, 1963). Unlike the prodines, however, cocaine contains a tropane nucleus and, therefore, may be considered to belong to a different subgroup. The present crystal structure analysis of *l*-cocaine hydrochloride provides direct confirmation of the stereochemical configuration of the cocaine molecule.

Crystal data and experimental procedure

The hydrochloride of *l*-cocaine ($C_{17}H_{21}O_4N$.HCl) was recrystallized from absolute ethanol as large irregular crystals. The crystals are orthorhombic with space

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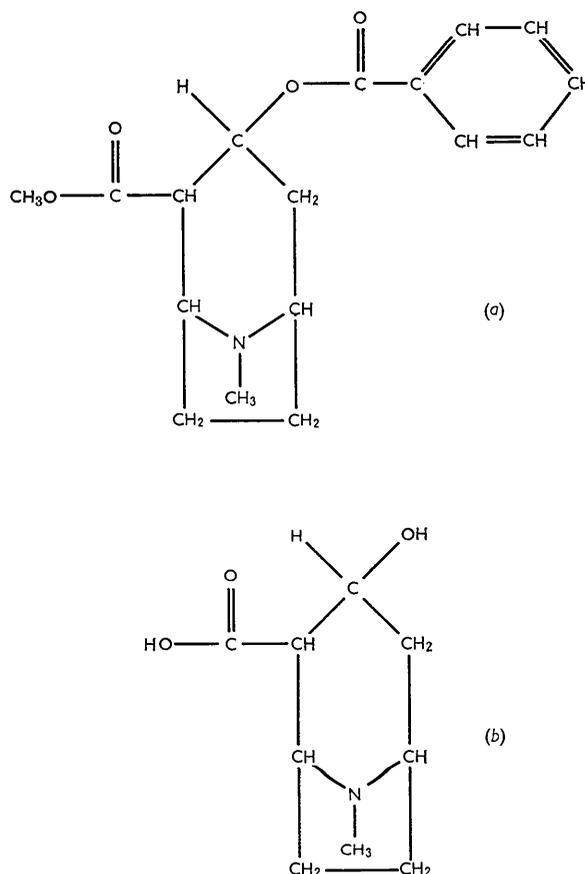
Fig. 1. (*a*) Cocaine; (*b*) ecgonine.

group $P2_12_12_1$, $a=7\cdot633\pm0\cdot001$, $b=10\cdot300\pm0\cdot001$, $c=21\cdot459\pm0\cdot003$ Å, $U=1686\cdot5$ Å³, F.W.$=339\cdot83$, $D_m=1\cdot342$ g.ml⁻¹ (21 °C, flotation in carbon tetrachloride–ether mixtures), $Z=4$, $D_c=1\cdot338$ g.ml⁻¹. The specimen employed for data collection was ground

into the form of a sphere of radius 0·019 cm for which $\mu R = 0·46$, and hence absorption was neglected.

The hydrobromide is isomorphous with the hydrochloride. It was recrystallized from absolute methanol but the crystals were of poor quality and only one small fragment suitable for data collection was obtained. The crystals are orthorhombic with space group $P2_12_12_1$, $a = 7·68 \pm 0·01$, $b = 10·68 \pm 0·01$, $c = 21·65 \pm 0·02$ Å, $U = 1775·8$ Å³, F.W. 384·29, (D_m not determined), $Z = 4$, $D_c = 1·437$ g.ml⁻¹.

For both salts, intensity data for the $0kl$ to $7kl$, and for the $h0l$, reflections were collected on a Nonius integrating Weissenberg camera. The use of 2·5 mm of horizontal integration for the upper levels made all diffraction spots effectively the same shape and size and no correction for distortion of the spots was necessary. The total number of observed reflections, however, was reduced by about 10% with this technique. The very weak reflections, therefore, were recorded without integration. Because most of these occurred in regions where the spot shape does not change rapidly ($\sin^2 \theta > 0·2$, approximately), no attempt to correct their estimated intensities for spot distortion was made. For the hydrochloride, 1735 of a possible 2050 reflections with $h < 8$ were observed.

The upper-level reflections were recorded with the equi-inclination method, and the corresponding zero level also was photographed on the same films with the anti-equi-inclination method by means of a double layer-line screen (Hanson, 1958). The intensities of the same 45 medium strong $0kl$ reflections were measured for each level, and, after application of the Lorentz and polarization corrections (Kartha, 1952), served to reduce the data for all levels to the same arbitrary scale. The Lp factors were applied to the equi-inclination data in the usual way, and all data were then placed on an approximately absolute scale (Wilson, 1942).

The atomic scattering-factor curves adopted for the calculation of structure factors were those of Freeman (1959) for C, N, O, and Cl⁻¹, and that of McWeeny (1951) for hydrogen.

Determination of the structure

The y and z co-ordinates of the heavy atom were determined from a Patterson map calculated with the $0kl$ data for the hydrobromide. Approximately 80% of all signs for this projection were fixed by the bromine contribution. An electron-density map calculated with these signs showed considerable detail and tentative positions were allocated to all atoms (with the exception of hydrogen). Structure factors calculated with these atomic co-ordinates showed $R = 0·33$. Several cycles of refinement by difference syntheses reduced R to 0·16, but it became necessary to move three atoms to new locations. No internal rearrangement of the molecule occurred but the

molecular orientation changed radically during refinement. Calculation of the $h0l$ Patterson function showed $x_{Br} = \frac{1}{4}$, so that the corresponding electron-density map for this zone could not be solved unambiguously.

The atomic co-ordinates derived from the last cycle of refinement of the $0kl$ zone of the hydrobromide were applied to the atoms of the hydrochloride and the $0kl$ electron-density projection of the latter was refined by successive cycles of difference syntheses to $R = 0·15_4$. A three-dimensional Patterson function was then calculated with the data for the hydrochloride sharpened by application of the zero-level Lp^{-1} function, and a vector convergence map was constructed. With the aid of the y and z co-ordinates derived from the $0kl$ projection, the x co-ordinates of all the light atoms were obtained from the vector convergence map. The first set of three-dimensional structure factors, calculated with $B = 3·5$ Å² for all atoms, gave $R = 0·28$ for all the observed data.

Three-dimensional refinement

Three-dimensional refinement of the structure of the hydrochloride was carried out in three cycles of electron-density calculations. A short routine was written for the IBM 1620 computer for the location of the centres of maximum concentration of electron density, and the evaluation of their curvatures and magnitudes, making use of the 27 points closest to each centre (Shoemaker, Donohue, Schomaker & Corey, 1950). The results obtained with this program agreed with those given by the differential synthesis method (Ahmed, 1961).

The first refinement cycle was performed with the observed data alone, 1·6 times the indicated shifts were applied, and a structure-factor calculation showed $R = 0·21_2$. Both F_o and F_c data were employed in the next cycle, and the shifts derived from the F_c-synthesis were used to correct for finite summation errors. The R-factor dropped to 0·13₄, and there was marked improvement in the molecular geometry, as a result of this cycle. A third cycle of refinement was calculated from which the final co-ordinates of all the light atoms (with the exception of hydrogen) were derived, in addition to an evaluation of a very slight degree of anisotropic thermal motion for the chlorine atom. At this stage, $R = 0·12_1$.

A routine was then written for the IBM 1620 computer for subtraction of the F_c Fourier results from those of F_o, and a three-dimensional difference synthesis was computed. The resulting maps showed electron-density maxima corresponding to all 21 hydrogen atoms of the cocaine molecule, at, or near, their theoretical positions. Structure factors were calculated for these atoms, with $B = 5·0$ Å², and the hydrogen-atom contributions were added to those of the other atoms. Unfortunately no clear evidence of

Table 1. *Fractional co-ordinates of all atoms except hydrogen*

Atom	x	y	z	r.m.s. $\{\sigma(x),\ \sigma(y),\ \sigma(z)\}$
C(1)	0·6756	−0·3503	0·3074	0·0070 Å
C(2)	0·5132	−0·2696	0·3276	0·0070
C(3)	0·5729	−0·1612	0·3736	0·0073
C(4)	0·7338	−0·0877	0·3507	0·0061
C(5)	0·8779	−0·1844	0·3292	0·0081
C(6)	0·9146	−0·2884	0·3781	0·0082
C(7)	0·7840	−0·4007	0·3642	0·0073
C(8)	0·3159	−0·1099	0·4307	0·0070
C(9)	0·1874	−0·0037	0·4433	0·0070
C(10)	0·1902	0·1162	0·4144	0·0088
C(11)	0·0660	0·2086	0·4291	0·0095
C(12)	−0·0588	0·1814	0·4731	0·0091
C(13)	−0·0661	0·0631	0·5011	0·0097
C(14)	0·0560	−0·0319	0·4872	0·0083
C(15)	0·4189	−0·2212	0·2704	0·0082
C(16)	0·3752	−0·2342	0·1628	0·0097
C(17)	0·9437	−0·3344	0·2428	0·0084
N	0·8062	−0·2619	0·2766	0·0053
O(1)	0·4442	−0·0716	0·3884	0·0051
O(2)	0·3152	−0·2125	0·4543	0·0078
O(3)	0·2994	−0·1384	0·2732	0·0067
O(4)	0·4572	−0·2791	0·2188	0·0052
Cl	0·7534	−0·0480	0·1788	0·0012

Table 2. *Fractional co-ordinates of the hydrogen atoms of the cocaine molecule*

Atom	x	y	z	Bonded to carbon atom
H(1)	0·630	−0·429	0·279	C(1)
H(2)	0·422	−0·337	0·347	C(2)
H(3)	0·595	−0·202	0·419	C(3)
H(4)	0·702	−0·025	0·313	C(4)
H(5)	0·790	−0·033	0·389	C(4)
H(6)	0·991	−0·131	0·313	C(5)
H(7)	0·050	−0·321	0·372	C(6)
H(8)	0·899	−0·248	0·423	C(6)
H(9)	0·700	−0·414	0·404	C(7)
H(10)	0·852	−0·487	0·352	C(7)
H(11)	0·289	0·137	0·381	C(10)
H(12)	0·071	0·302	0·407	C(11)
H(13)	−0·153	0·254	0·484	C(12)
H(14)	−0·166	0·042	0·535	C(13)
H(15)	0·050	−0·123	0·510	C(14)
H(16)	0·309	−0·308	0·133	C(16)
H(17)	0·450	−0·159	0·142	C(16)
H(18)	0·283	−0·192	0·183	C(16)
H(19)	0·050	−0·350	0·275	C(17)
H(20)	0·850	−0·392	0·217	C(17)
H(21)	0·008	−0·258	0·225	C(17)

Table 3. *Observed and calculated electron densities* (e.Å^{-3}), *mean curvatures* (e.Å^{-5}), *and isotropic B values* (Å^2)

Atom	ϱ_o	ϱ_c	ϱ_o''	ϱ_c''	B
C(1)	8·7	8·4	76·7	72·0	3·0
C(2)	8·6	8·5	76·3	78·9	3·4
C(3)	8·4	8·3	72·9	73·1	3·4
C(4)	9·0	8·9	86·6	85·4	3·0
C(5)	8·0	7·9	65·8	64·4	3·4
C(6)	7·8	8·2	64·6	73·3	3·6
C(7)	8·2	8·3	72·4	76·2	3·4
C(8)	8·4	7·8	76·2	63·6	3·4
C(9)	8·5	8·2	77·9	69·8	3·2
C(10)	7·6	7·6	62·8	61·7	3·8
C(11)	7·2	7·5	56·7	59·8	4·0
C(12)	7·4	7·5	59·1	59·5	3·8
C(13)	7·1	7·4	56·2	61·1	4·3
C(14)	7·8	7·7	65·2	63·6	3·7
C(15)	8·1	7·4	65·8	51·6	3·0
C(16)	7·0	7·0	54·7	56·7	4·1
C(17)	7·8	7·7	64·1	66·6	3·8
N	11·3	10·7	101·5	92·7	2·8
O(1)	12·1	12·1	105·5	100·5	3·5
O(2)	10·0	10·4	69·1	73·1	4·2
O(3)	10·4	10·9	80·0	86·3	4·3
O(4)	12·4	12·2	102·0	102·3	3·5
Cl	36·7	37·9	442·7	468·1	3·25

Table 4. *Agreement summary*

1735 observed reflections* (0·9 ≤ |F_o| ≤ 133·8)

Category	Limits		Number
1	|ΔF| ≤ 2·0, or	|ΔF|/|F_o| ≤ 0·2	1547
2	2·0 < |ΔF| ≤ 4·0, or	0·2 < |ΔF|/|F_o| ≤ 0·4	168
3	4·0 < |ΔF| ≤ 6·0, or	0·4 < |ΔF|/|F_o| ≤ 0·6	16
4	6·0 < |ΔF| < 8·0, or	0·6 < |ΔF|/|F_o| < 0·8	4

315 unobserved reflections ($h < 8$)

Category	Limits	Number
1	|F_c| ≤ 2·0	153
2	2·0 < |F_c| ≤ 4·0	111
3	4·0 < |F_c| ≤ 6·0	34
4	6·0 < |F_c| ≤ 8·0	12
5	8·0 < |F_c| < 10·0	5

* All observed reflections have been classified into four categories according to selected limits for |ΔF| = ||F_o| − |F_c|| and |ΔF|/|F_o|. For about 70% of the present data, each reflection falls into the same category on the basis of either criterion. For the rest of the data, each reflection falls into two categories on this basis, and it has been included in the total number for the lower category only. This makes allowance for the fact that |ΔF| may be large for a very strong reflection even when |ΔF|/|F_o| is satisfactorily low, while |ΔF|/|F_o| may be misleadingly high for a very weak reflection for which |ΔF| is, in fact, satisfactorily small.

the location of the hydrogen atom associated with the chlorine in the hydrochloride appeared in the final difference synthesis.

The data from all levels were corrected for small changes in scale, the contributions of all hydrogen atoms (with the exception of that of the HCl) were included in F_c, and the final $R = 0\cdot10_5$ for all the observed reflections.

The fractional co-ordinates of all atoms (excluding the hydrogens) are given in Table 1, while those of the hydrogen atoms of the cocaine molecule are listed in Table 2. The final observed and calculated electron-

density maxima, mean principal curvatures, and temperature-factor constants are shown in Table 3. A complete list of observed structure amplitudes and calculated structure factors is not included, but may be obtained from the authors on request. A summary of the agreement between |F_o| and |F_c| (Hanson & Ahmed, 1958) for both the observed and unobserved reflections, however, is presented in Table 4, where it may be noted that only 20 observed reflections are

in the two categories of higher discrepancies, but all have $|F_o| < 12 \cdot 0$, while, for all the unobserved reflections for which $h < 8$, $|F_c| < 10 \cdot 0$.

Discussion

The mean standard deviations of the atomic co-ordinates, calculated with the formula of Cruickshank (Lipson & Cochran, 1953), are $0 \cdot 0078$ Å for C,

0·0060 Å for N and O, and 0·0012 Å for Cl. Hence the standard deviation of a bond length within the cocaine molecule is 0·011 Å, and that of a bond angle is 0·6°, approximately. Therefore, differences > 0·025 Å in bond lengths, and > 1·5° in bond angles, between observed and generally accepted values, may be considered as significant. Observed intramolecular bond lengths and angles are shown in Fig. 2, and a perspective drawing of the cocaine molecule is reproduced in Fig. 3.

Fig. 3. Perspective view of the molecule of cocaine.

In the cocaine molecule, as it appears in the crystal structure of l-cocaine hydrochloride, the piperidine ring has the chair form with the CH_3 on N, and the benzoxy side-chain on C(3), in equatorial positions, and the carbomethoxy side-chain on C(2) in an axial position. Thus the substituents on C(2) and C(3) are *cis* to each other and to the N. This fully confirms the latest deductions about the stereochemical configuration of l-cocaine if the CH_3 on N in diagram XVIII of Fodor (1960), for example, is shown in an equatorial (instead of an axial) position and R is replaced by CH_3.

The C–C bond lengths in the benzene ring and the tropane nucleus are close to normal values (Sutton, 1958), as are the C–N bonds and C–N–C angles of the piperidine ring (Rérat, 1960; Kartha, Ahmed & Barnes, 1960, 1962; Ahmed, Barnes & Masironi, 1963). The C(8)=O(2) bond (1·17 Å) is slightly shorter than the usual value of 1·23 Å (Sutton, 1958) but a comparable length (1·19 Å) has been found in dl-beta-prodine hydrobromide (Ahmed, Barnes & Masironi, 1963). The two bonds, O(1)–C(3) = 1·38 Å and O(4)–C(16)=1·43 Å, are both shorter than 1·48 ± 0·03 Å, the mean of comparable bonds in dl-alpha-prodine hydrochloride (Kartha, Ahmed & Barnes,

Fig. 2. Intramolecular bond lengths (Å) and bond angles (°).

1960), *dl*-betaprodine hydrobromide (Ahmed, Barnes & Masironi, 1963), annotinine bromohydrin (Przybylska & Ahmed, 1958), shellolic bromolactone hydrate (Gabe, 1962), methyl formate, methyl acetate, and diethyl terephthalate (Sutton, 1958). Also, on the basis of the foregoing structures, one would expect $C(15)-O(4) < O(4)-C(16)$ as is in fact the case, and $C(8)-O(1) < O(1)-C(3)$ which, however, is not observed in the present structure.

In *dl*-alphaprodine hydrochloride, *dl*-betaprodine hydrobromide, and codeine hydrobromide dihydrate (Kartha, Ahmed & Barnes, 1962) the distances across the piperidine ring from atoms corresponding to $C(2)$ and $C(4)$, and to $C(1)$ and $C(5)$, are about 2·51 Å and 2·48 Å, respectively. The introduction of the ethylene bridge from $C(1)$ to $C(5)$ in the cocaine molecule has increased the former to 2·57 Å and has markedly reduced the latter to 2·35 Å. The corresponding values calculated for the tropine molecule in tropine hydrobromide (Visser, Manassen & deVries, 1954) are 2·58 Å and 2·44 Å, respectively. In tropine the carbomethoxy group on $C(2)$ is not present, and the benzoxy group on $C(3)$ is replaced by OH which is *trans* to the N.

The best plane through $C(1)$, $C(2)$, $C(4)$, and $C(5)$ of the piperidine ring (see Fig. 3) is given by the equation

$$0\cdot0946X + 0\cdot3371Y + 0\cdot9367Z - 7\cdot8883 = 0 , \quad (1)$$

where X, Y, and Z are in Å. The distances of the four atoms from this plane are $+0\cdot0041$, $-0\cdot0040$, $+0\cdot0038$, and $-0\cdot0043$ Å, respectively. Also, for each of the two sets of atoms, N, $C(1)$, $C(3)$, $C(4)$ and N, $C(2)$, $C(3)$, $C(5)$, the atomic positions are within one standard deviation of the mean planes. That the piperidine ring is in the chair form is shown by the fact that $C(3)$ and N are on opposite sides of the plane represented by equation (1). A further effect of the bridge between $C(1)$ and $C(5)$ is to increase the distance of N to $-0\cdot8106$ Å, and decrease the distance of $C(3)$ to $+0\cdot5949$ Å, from the plane through $C(1)$, $C(2)$, $C(4)$, and $C(5)$, compared with equal distances of about $0\cdot727$ Å on opposite sides of the plane to be expected in an unbridged piperidine ring.

The best plane through the atoms $C(1)$, $C(5)$, $C(6)$, and $C(7)$, involved in the bridge across the piperidine ring, is given by the equation

$$0\cdot6616X - 0\cdot4230Y - 0\cdot6191Z - 0\cdot8625 = 0 , \quad (2)$$

and the four atoms are at distances of $+0\cdot0042$, $-0\cdot0054$, $+0\cdot0073$, and $-0\cdot0059$ Å, respectively, from this plane. The nitrogen atom is $0\cdot6619$ Å from plane (2), and the angle between planes (1) and (2) is $112\cdot0°$.

The best plane through the benzene ring is given by the equation

$$0\cdot5954X + 0\cdot3454Y + 0\cdot7255Z - 7\cdot7316 = 0 , \quad (3)$$

and $C(9)$, $C(10)$, $C(11)$, $C(12)$, $C(13)$, and $C(14)$ are at

distances $+0\cdot0084$, $-0\cdot0023$, $-0\cdot0089$, $+0\cdot0124$, $-0\cdot0057$, and $-0\cdot0054$ Å, respectively, from this plane. The benzene ring, therefore, is planar within the limits of accuracy of the present investigation. The plane through atoms $O(1)$, $C(8)$, $O(2)$, and $C(9)$ is almost coincident with that of the benzene ring, with the normals to the two planes at an angle of only 1·7°. The benzene ring makes an angle of 31·5° with the plane of the piperidine ring defined by $C(1)$, $C(2)$, $C(4)$, and $C(5)$. The atoms $C(2)$, $C(15)$, $O(3)$, and $O(4)$ of the other side-chain also are nearly co-planar.

The Cl is only $3\cdot06_9$ Å from the N, and this immediately suggests the presence of an H-bond between them. The pertinent angles are $C(1)-N-Cl = 100\cdot5°$, $C(5)-N-Cl = 130\cdot4°$, $C(17)-N-Cl = 96\cdot9°$, $C(1)-N-C(5) = 103\cdot6°$, $C(1)-N-C(17) = 112\cdot5°$, $C(5)-N-C(17) = 112\cdot4°$ (mean, 109·4°). It is unfortunate that no indication of the site of the H of the HCl appeared in the final difference synthesis but it is possible that it is off the line joining N and Cl in a direction such that the angles $C(5)-N-H$ and $C(17)-N-H$ are closer to the tetrahedral value. With $-COOCH_3$ on $C(2)$ in an axial position and $-OCOC_6H_5$ on $C(3)$ equatorial, the *cis* relationship of these two substituents must involve some interaction between $O(3)$ of the first and $O(1)$ of the second and rotation of the $O(3) = C(15)-O(4)-C(16)H_3$ side-chain around the $C(2)-C(15)$ bond into an equilibrium position, which, in the present structure, appears to be reached with $O(3)-O(1) = 2\cdot79$ Å. This brings $O(4)$ to 2·63 Å from $C(1)$, and 3·38 Å from Cl, and has the effect of reducing the angle $C(17)-N-Cl$ below the normal value for an undistorted tetrahedral arrangement of bonds to the N. At the same time the presence of an adjacent cocaine molecule with closest approach of 3·52 Å from $C(2)$ to the same Cl results in an increase in the angle $C(5)-N-Cl$.

References

AHMED, F. R. (1961). *Crystallographic Computations. Part I. Generalized Structure Factor Program for the Basic IBM 650 Computer (Report No. 6333); Part II. Differential Synthesis Program for the Basic IBM 650*

Computer (*Report No.* 6478). Ottawa: National Research Council.

AHMED, F. R., BARNES, W. H. & MASIRONI, L. DI M. (1963). *Acta Cryst.* **16**, 237.

FARMILO, C. G. & LEVI, L. (1953). *Bull. Narcotics, U.N. Dept. Social Affairs*, **5** (4), 20.

FODOR, G. (1960). in MANSKE, R. H. F. *The Alkaloids*, vol. VI, chap. 5. New York: Academic Press.

FREEMAN, A. J. (1959). *Acta Cryst.* **12**, 261.

GABE, E. J. (1962). *Acta Cryst.* **15**, 759.

HANSON, A. W. (1958). *J. Sci. Instrum.* **35**, 180.

HANSON, A. W. & AHMED, F. R. (1958). *Acta Cryst.* **11**, 724.

HOLMES, H. L. (1950) in MANSKE, R. H. F. & HOLMES, H. L. *The Alkaloids*, vol. I, chap. VI. New York: Academic Press.

KARTHA, G. (1952). *Acta Cryst.* **5**, 549.

KARTHA, G., AHMED, F. R. & BARNES, W. H. (1960). *Acta Cryst.* **13**, 525.

KARTHA, G., AHMED, F. R. & BARNES, W. H. (1961). *Acta Cryst.* **14**, 93.

KARTHA, G., AHMED, F. R. & BARNES, W. H. (1962). *Acta Cryst.* **15**, 326.

LIEBERMANN, C. (1890). *Ber. Dtsch. Chem. Ges.* **23**, 2518.

LIPSON, H. & COCHRAN, W. (1953). *The Determination of Crystal Structures.* London: Bell.

McWEENY, R. (1951). *Acta Cryst.* **4**, 513.

MERCK, W. (1885). *Ber. Dtsch. Chem. Ges.* **18**, 2952.

PRZYBYLSKA, M. & AHMED, F. R. (1958). *Acta Cryst.* **11**, 718.

RÉRAT, C. (1960). *Acta Cryst.* **13**, 72.

SHOEMAKER, D. P., DONOHUE, J., SCHOMAKER, V. & COREY, R. B. (1950). *J. Amer. Chem. Soc.* **72**, 2328.

SUTTON, L. E. (1958). *Tables of Interatomic Distances and Configurations in Molecules and Ions.* London: The Chemical Society.

VISSER, J. W., MANASSEN, J. & DEVRIES, J. L. (1954). *Acta Cryst.* **7**, 288.

WILLSTÄTTER, R., WOLFES, O. & MÄDER, H. (1923). *Liebigs Ann.* **434**, 111.

WILSON, A. J. C. (1942). *Nature, Lond.* **150**, 152.

WÖHLER, F. (1862). *Ann. Chem. Pharm.* **121**, 372.

Second Review of Al-O and Si-O Tetrahedral Distances

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In the same tetrahedron, individual Si-O (or Al-O) distances have been found to vary by amounts up to 0·1 Å even when the random experimental error is less than 0·01 Å. In a single structure the differences between the mean values of the four distances in a tetrahedron are much smaller, for variations between chemically identical tetrahedra rarely amount to more than 0·02 Å. The average of all the Si-O distances in a structure depends on the extent of the tetrahedral linkage, changing from 1·61 Å in frameworks to 1·63 Å in structures with isolated tetrahedra. Correspondingly, the average Al-O distance changes from 1·75 to 1·80 Å, the latter figure requiring confirmation. The mean tetrahedral distance in a feldspar structure varies linearly with percentage Al from 1·61 for Si-O to 1·75 Å for Al-O. Individual tetrahedral means for ordered structures confirm these end values. The deviations from linearity are not greater than 0·003 Å and may merely result from random experimental error. Mean values for other framework structures deviate from the linear relation by about 0·01 Å. The less accurate data for layer silicates suggest a linear relation for the overall mean Si, Al-O distance between Si-O 1·62 and Al-O 1·77 Å.

Estimation of the Al-content of an individual tetrahedron from the measured Si, Al-O distances must take into account the effects of structural type and of local environment of the tetrahedron. Even after correction for the structural type, it seems that the local environment may lead to errors of ±5% Al (in round figures) in addition to the effect of experimental error.

It is hoped that further studies along these lines may lead to empirical relations between bond distances and atomic environment for complex structures, and ultimately to estimation of the internal energy from observed atomic coordinates.

1. Introduction

In 1954 J. V. Smith examined measured Si, Al-O distances and suggested standard values for estimating the substitution of aluminum and silicon atoms in tetrahedra. The available data were mainly of low accuracy and the predicted values (Si-O, 1·60; Al-O, 1·78 Å) were somewhat uncertain. Nevertheless, these values have been used considerably in discussion of feldspar structures, sometimes without full awareness