Studies in the Crystal and Molecular Structure of Heterocyclic Compounds.

Part I - Furoic Acid

Part II - 2:5 Dicyano 3:6 Dimethyl Pyrazine.

THESIS

presented for the Degree of

Doctor of Philosophy

at

The University of Glasgow

by

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April, 1951.

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PART I - FUROIC ACID

PART II - 2:5 DICYANO 3:6 DIMETHYL PYRAZINE.

Preface.

The first part of this work is being prepared for publication in collaboration with Dr. T.H. Goodwin, to whom I am indebted for suggesting both the problems investigated in this Thesis.

I should like also to express my sincere thanks to Dr. Goodwin for his constant interest, encouragement and advice throughout this work, and to Professor Robertson for helpful discussion.

I am grateful to Professor F.S. Spring for the sample of 2:5 dicyano 3:6 dimethyl pyrazine and to Imperial Chemical Industries Ltd. for the sample of furoic acid.

I also wish to thank the Department of Scientific and Industrial Research for a Maintenance Allowance.

Summary.

The crystal and molecular structures of furoic acid and of 2:5 dicyano 3:6 dimethyl pyrazine have been investigated by methods of X-ray analysis.

Part I. Furoic Acid.

The unit cell of furoic acid was measured from rotation photographs about each of the unit cell axes and found to be $a = 10.24\text{Å}$; $b = 6.80\text{Å}$; $c = 3.81\text{Å}$ with $\alpha = 92^\circ 57'$; $\beta = 94^\circ 16'$; $\gamma = 106^\circ 10'$. The crystals therefore were classified as triclinic. From the observed density, the number of molecules in the unit cell was calculated to be two. Moving film photographs about each of the three unit cell axes showed no systematic absences; the space group was assumed to be $P\bar{1}$, and this assumption was later found to be justified.

Observed structure factors for all planes having $2 \sin \theta < 2$ in the (hko), (hol) and (okl) zones were calculated from the estimated intensities of reflections recorded on multiple film series.

The preliminary investigation of the structure of furoic acid was carried out by trial structure methods; the coordinates of trial structures in which reasonable agreement between observed and calculated structure factors was found, were refined by two-dimensional Fourier syntheses.

The final coordinates obtained from the investigation

are listed. Structure factors calculated from these coordinates showed discrepancies of 12.1%, 16.9% and 12.8% for all planes in the (hko), (hol) and (okl) zones respectively.

The bond lengths calculated from these coordinates are discussed; they show that considerable resonance takes place within the ring, and between the ring and the carboxyl group. Hydrogen bonds link the carboxyl groups of two adjacent molecules. The furan ring was found to be planar, with the plane of the carboxyl group inclined to the plane of the ring at an angle of 20°.

Part II. 2:5 dicyano 3:6 dimethyl pyrazine.

The unit cell dimensions of 2:5 dicyano 3:6 dimethyl pyrazine were measured from rotation photographs and found to be, a = 6.14Å; b = 8.71Å; c = 15.43Å, with $\alpha = \beta = \gamma = 90^\circ$. The crystal system was therefore orthorhombic; this was confirmed by an examination of the symmetry of oscillation photographs taken about each of the unit cell axes.

Moving film photographs showed systematic absences of reflections which indicated that the space group was P_{bca}. From the observed density, the number of molecules in the unit cell was calculated to be four.

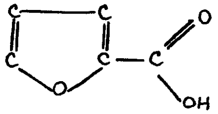
Observed structure factors were calculated from the intensities of planes recorded on multiple film series for the (hol) zone. The structure was investigated by trial structure methods, followed by refinement by Fourier and "error" syntheses.

The results of the investigation at present indicate that the plane of the molecule is inclined to the b-axis at an angle of about 30°. A trial structure in this projection showed a discrepancy of 30.6%. Improvement of this discrepancy to 25.1% was noted when an approximate estimate of the contribution of the hydrogen atoms was included.

It is hoped that refinement will be possible by Fourier and "error" syntheses methods.

Part I.

The Crystal and Molecular Structure
of
Furoic Acid.



Introduction.

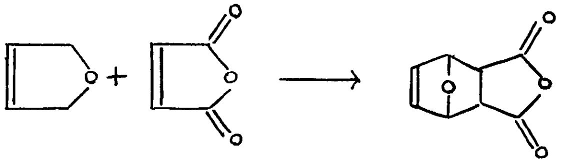
Few heterocyclic oxygen-containing compounds have been studied by X-ray analysis. An investigation of the structure of the sodium bromide dihydrate of sucrose[1] has been carried out in recent years, but, apart from this, little detailed work has been recorded. The present investigation was concerned with the structure of furanose compounds. The parent compound, furan C_4H_4O, is a liquid of low boiling point, and is thus unsuitable for investigation by X-ray methods. It has, however, been investigated by both spectroscopic and electron diffraction experiments.

Examination of the infra-red spectrum[2,3,4], combined with Raman spectrum results[5], and of the ultraviolet absorption spectrum of furan[6,7,8] showed that the observed bands could be explained on the basis of a planar model with symmetry described in group analysis as C_{2v}. In recent infra-red investigations[3], attempts were made to correlate the observed rotational contours of the bands with values for the moment of inertia, which differs for planar and buckled molecular structures. It was found that definite conclusions could not be drawn, since the change in moment of inertia for slight buckling was not very marked.

While quantitative results have not been obtained from spectroscopic analysis, it has been possible to find some evidence of the nature of the bonds in the ring. An examination of the absorption spectra of some esters and amides of furan[9] showed that the furan nucleus acted as an acyclic system of double bonds in that any addition to the conjugated system displaced the absorption curve and maximum towards a longer wavelength. On the other hand, when an acyclic system was replaced by a furan nucleus, the displacement of the spectrum was only about half as much, indicating that the furan nucleus was not entirely acyclic.

More detailed structural analyses of furan have been carried out by Pauling and Schomaker[10] and by Beach[11]. In both cases, the carbon to carbon bond distances in the ring were assumed, by analogy with cyclopentadiene, and the carbon to oxygen distances calculated from data obtained by electron diffraction experiments. They found that there was considerable shortening of all the bond lengths from single-bond lengths, and Pauling and Schomaker[10] suggested that this was due to contributions from resonance structures making use of the unshared electron pair on the ring oxygen atom.

Chemically, the effect of this extra resonance is shown in the many aromatic properties of furan. This compound is intermediate in properties between a conjugated diene and an a aromatic hydrocarbon. It reacts like a conjugated diene with maleic anhydride



In other reactions it shows aromatic properties, e.g., it undergoes bromination, nitration, sulphonation and catalytic hydrogenation. Indeed, at one time, furan was considered to have "superaromatic" properties compared with benzene because of its greater ease of halogenation and nitration, and the selective cleavage of the organic lead compounds[12]. However, a study of the amines of furan[13] showed that these compounds did not possess many of the characteristic reactions of aromatic amines such as ease of hydrolysis by aqueous acids and alkalies and diazotisation. Furan must, therefore, have weaker aromatic properties than benzene.

An alternative theory to account for the relative ease of substitution of furan compared with benzene was postulated from a study of the directing effect of substituents in the furan ring. The characteristic directing effect of aromatic substituents is conspicuously ineffective in furan. When opposed by tendency towards substitution in the α-position, even the strong m-directing sodium ion fails to exert any influence on the furan nucleus[14]. Such a failure in an aromatic system is usually due to the presence of a strong ortho-para-directing influence such as that of an ether (methoxy) group. The suggestion has therefore been made that furan is an internal ether of a diene which exhibits sensitivity to acids and alkalies in common with all ethers and shows additive reactions and 1:4 addition peculiar to dienes.

The transference of the oxygen into the ring should intensify the usual activating influence of the ether group, and therefore the enhancement of those properties such as labilising the o-hydrogen atom giving formal electronegativity to the o-carbon atom leads to easier substitution, predominantly in the ortho- (i.e., α -) position.

An accurate determination of the structure of furan and its derivatives should, therefore, be of interest in determining the nature and extent of these various influences in the molecule.

Since furan is a liquid of low boiling point (32°C), it was unsuitable for X-ray analysis. A solid, of reasonable stability, was required, and the derivative, α -furoic acid, or pyromucic acid, $C_5H_4O_3$, seemed suitable. It could be obtained as a crystalline solid of fairly high melting point (133°C). An investigation of the structure of this compound by the methods of X-ray analysis was, therefore, carried out.

EXPERIMENTAL.

1) Preparation.

The sample of furoic acid was obtained from Imperial Chemical Industries Ltd. as a brown amorphous powder. Purification was carried out by treatment with animal charcoal and slow crystallization from hot water. Colourless, plate-like crystals, m.p. 133°C were obtained in this way and repeated attempts to obtain crystals equally developed in all directions were unsuccessful.

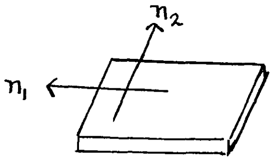
2) Optical Examination.

a). Microscopic Examination showed that the crystals were tabular with striations in most cases parallel to the shorter edge. Aggregations occurred in many cases, but these were visible under the microscope, and single crystals could be chosen in this way. Highly developed cleavage was noted perpendicular to the plane of the plate.

b). Extinction was noted at 56° to the length of the plate.

c). Refractive Indices were measured by the Becke line method in the two directions in the plane of the plate. It was impracticable to measure the third index with the apparatus available, because of the thinness of the plates. The refractive indices for light polarised in the directions shown in the diagram were

$n_1 = 1.384 \pm .004$
$n_2 = 1.688 \pm .004$
$n_1 - n_2 = 0.304$



Birefringence was therefore at least 0.304, a very high value.

d). The Crystal System of furoic acid was determined by Groth[15] from optical investigations; he found that furoic acid belonged to the monoclinic system with angle $\beta = 113^\circ 44'$ and axial ratios of $a:b:c = .9556:1:.5259$. The present investigation by X-ray methods has shown that the crystals of furoic acid belong to the triclinic system with angles α and γ very nearly 90°.

3) Density.

The density was measured by flotation in a mixture of benzyl chloride and carbon tetrachloride to be 1.483 gm./ml.

4) X-ray Investigation.

a). Apparatus.

All experiments were carried out using copper targets giving $CuK\alpha$ radiation ($\lambda = 1.54$Å); the $CuK\beta$ radiation was removed by means of a nickel filter. Rotation and oscillation photographs were taken with cameras of radius 3.00 cms. Moving film photographs were taken on a horizontal Weissenberg apparatus with cameras of radius 3.94 cms. and 3.99 cms.; in each case the camera angle was 70°. Oscillation was about 200° with camera travel about 9 cms.

b). Dimensions of Crystals.

The average size was 0.8 mm. long and 0.33 mm. x 0.1 mm. in cross-section.

c). Photographs.

Rotation and oscillation photographs were taken about the three unit cell axes. For the evaluation of the structure by two-dimensional Fourier methods zero layer moving films and multiple film series were taken about each of the three axes.

d). Unit cell dimensions.

$a = 10.24Å \pm .02Å$ $b = 6.30Å \pm .02Å$ $c = 3.81Å$

$\alpha = 92^\circ 57'$ $\beta = 94^\circ 16'$ $\gamma = 106^\circ 10'$

These values gave reciprocal cell dimensions as follows

$a^* = .1571$ $b^* = .2361$ $c^* = .4063$

$\alpha^* = 85^\circ 41'$ $\beta^* = 84^\circ 42'$ $\gamma^* = 73^\circ 27'$

Volume of unit cell = 253.3 cuÅ

Number of molecules in unit cell = 2

Density calculated = 1.469 g/ml.

Density observed = 1.483 g/ml.

e). Location of Axes.

Since the crystals were triclinic and were obtained in the form of thin plates, some difficulty was experienced in locating the axis at right angles to the plane of the plate. Several axes of similar length were found, e.g., 10.24Å, 10.72Å, 19.3Å, 19.5Å and this complicated matters also. The true axis was located, using a stereographic projection on which arc readings for known axes could be plotted and those for the required axis then found.

f). Space Group.

Oscillation photographs about each of the three axes showed no symmetry; moving film photographs about each of the three axes showed no absent spectra.

It was therefore concluded that furoic acid was to be classified in the triclinic system. There are two space groups in this system, viz. $P_1(C_1^1)$ having no symmetry and $P\bar{1}(C_1^1)$ having a centre of symmetry. Since a centre of symmetry gives rise to no systematic absences of reflections, no distinction can be made between the two space groups by X-ray analysis. Though the molecule of furoic acid has no centre of symmetry, there could be symmetry between two molecules and so the space group $P\bar{1}$ is not impossible.

Absence of a centre of symmetry in a crystal may sometimes be detected by physical methods.

(i) Pyroelectric method.

When crystals in which there is no centre of symmetry are heated or cooled, they develop unlike electric charges at opposite ends of each polar axis. J.M. Robertson[16] carried out pyroelectric tests by suspending side by side two crystals by fine silk fibres in liquid air. Non-centrosymmetric crystals were attracted to each other; centrosymmetric crystals were not. With this apparatus, weak pyroelectricity might not be detected and so only a positive result would be definite.

In the case of furoic acid, no pyroelectric effect was detected.

(ii) Piezoelectric method.

When a potential difference is applied to a non-centrosymmetric crystal at a suitable point, the crystal expands or contracts. For this experiment[46], crystals about 1 cm. long were obtained by slow cooling of a saturated aqueous solution of furoic acid. Tests were carried out along the three principal directions, but no piezoelectric effect was found.

As in the case of the pyroelectric effect, weak piezoelectric effects might not be detected by the apparatus, though the latter is the more sensitive.

These experiments, then, seem to indicate the presence of a centre of symmetry, but do not establish this unequivocally. In the first instance, however, the space group was assumed to be $P\bar{1}$, but the possibility that it was $P1$ was noted.

Structure Determination.

The determination of the structure of furoic acid was carried out by the trial structure method, followed by refinement by two dimensional Fourier syntheses. The method may be divided into four sections.

1). The observed intensities of reflections in each of the three zones (hko), (hol) and (okl) are measured and the observed structure factors calculated for all planes having $2\sin\theta \leq 2.00$.

2). A trial structure is postulated, theoretical structure factors calculated and compared with the corresponding observed structure factors.

3). For a trial structure giving reasonable agreement between observed and calculated structure factors, Fourier syntheses are carried out projecting down each axis in turn and an electron density "contour" map for the projection is drawn. Theoretical structure factors are then calculated from atomic coordinates estimated from the projections, and the procedure repeated until the structure factors show no change in sign.

4). Structure factors for all planes are calculated from the coordinates chosen from the final Fourier syntheses, and the discrepancies found.

A. Investigation of (hko) zone.

Because of the very short c-axis, it was thought that resolution of the atoms would probably be greatest in the projection along this axis.

Observed Structure Factors.

Intensities of reflections in the (hko) zone were estimated by the multiple film technique[17]. The films used had film ratio of 3 and, to give a wide range of intensities, two series, one of five films and one of three films, were taken. The second series was given an exposure of $^{1}/_{3}{}^{5}$ times the exposure of the first. In the (hko) zone, 70% of the planes within the limiting circle of reflection were recorded, and a list of comparative intensities was prepared.

The range of intensities was approximately 2,000 to 1.

These intensities were corrected for the following factors:

a) polarization of the X-ray beam

b) Lorentz correction.

a) and b). Polarization and Lorentz factor.

Both of these factors vary with the 2 sin θ of a plane, and tables of correction for the combined effect of these factors for various 2 sin θ values have been drawn up from data in Internationalle Tabellen[18]. When these corrections had been applied, the observed structure factor, $F_{obs.}$, was calculated.

$$F_{obs} = \pm \sqrt{I_{corr.}}$$

The magnitude of the structure factor could thus be calculated, but not its sign. Since there were no heavy atoms in the projection along this axis.

Observed Structure Factors.

Intensities of reflections in the (hko) zone were estimated by the multiple film technique[17]. The films used had film ratio of 3 and, to give a wide range of intensities, two series, one of five films and one of three films, were taken. The second series was given an exposure of $^1/_35$ times the exposure of the first. In the (hko) zone, 70% of the planes within the limiting circle of reflection were recorded, and a list of comparative intensities was prepared.

The range of intensities was approximately 2,000 to 1.

These intensities were corrected for the following factors:

a) polarization of the X-ray beam

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$$F_{obs} = \pm \sqrt{I_{corr.}}$$

The magnitude of the structure factor could thus be calculated, but not its sign. Since there were no heavy atoms in the molecule which would help to decide the signs, the method of postulating trial structures in accordance with other evidence was adopted.

The values of the structure factors were not placed on an absolute scale, but were scaled by comparison with calculated structure factors later.

2). Trial Structures and Calculation of Theoretical Structure Factors.

a). Dimensions of the Molecule.

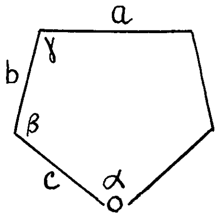
In order to postulate a trial structure, it was necessary to have an idea of the dimensions of the furoic acid molecule.

(i) Furan Ring.

Schomaker and Pauling[10], from electron diffraction experiments give the following results:-

Assumed $a = 1.46\text{Å}$, $b = 1.35\text{Å}$. Calculated $c = 1.41\text{Å} \pm .03\text{Å}$

$\alpha = 107^{\circ} \pm 4^{\circ}$ $\beta = 109^{\circ} \pm 3^{\circ}$ $\gamma = 107^{\circ} \pm 2^{\circ}$



Beach[11], by the same method, obtained results in agreement with those quoted, viz.,

Assumed $a = 1.46\text{Å}$, $b = 1.35\text{Å}$. Calculated $c = 1.40 \pm .03\text{Å}$

$\alpha = 107 \pm 3^{\circ}$.

In both cases, the ring was found to be planar within experimental error. Spectroscopic examination also led to this conclusion, as discussed in the Introduction.

(ii). Carboxyl Group.

Bond lengths in the carboxyl group have been determined in many different compounds. For the formic acid and acetic acid dimers, values found by Karle and Brockway[19] for the carbon to oxygen bonds were 1.36Å and 1.25Å. In the study of some dicarboxylic acids, J.M. Robertson and his coworkers gave the following results:-

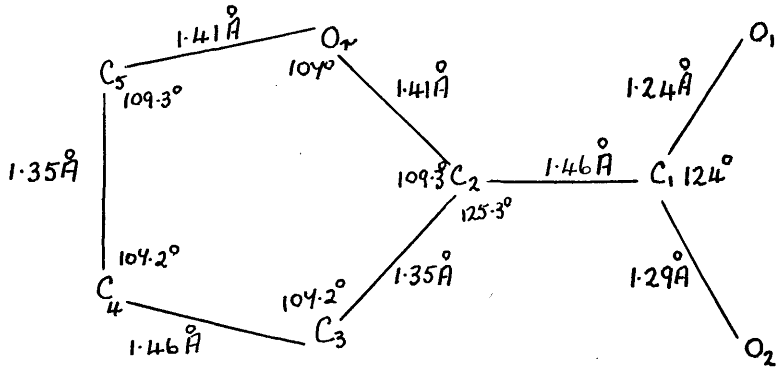
Acid	$C-O_2$(Å)	$C-O_1$(Å)	$O_1-\hat{C}-O_2$(°)	H bond (Å)
Oxalic acid dihydrate[20]	1.25	1.24		2.50
Acetylene dicarboxylic acid dihydrate[21]	1.27	1.26	123	2.56
Diacetylene dicarboxylic acid dihydrate[22]	1.25	1.25	123.5	2.55
β -succinic[23]	1.30	1.25	122	2.64
Adipic[23]	1.29	1.23	126	2.68
Sebacic[23]	1.27	1.24	124	2.68
β-glutaric[23]	1.30	1.23	122	2.69

It was probably best to compare the carboxyl group of furoic acid with that of oxalic acid, but, as the latter was determined as the dihydrate, it was decided to assume the dimensions of the carboxyl group as an average of the dicarboxylic acid dimensions, viz:-

$C_1-O_2 = 1.29$Å; $C_1-O_1 = 1.24$Å; $O_1\hat{C}_1O_2 = 123°$, with the hydrogen bond distance between carboxyl groups of adjacent molecules 2.66Å.

(iii). Extracyclic carbon to carbon bond.

Several resonance structures for furoic acid may be written in which the extracyclic carbon to carbon bond is a formal double bond, so that some shortening of this bond from the single bond value is likely. By analogy with oxalic acid dihydrate[20], it was decided to assume a length of 1.46Å for this bond. Thus, the following values were taken for preliminary investigation as the dimensions of the furoic acid molecule.



b) <u>Factors indicating position of the molecule.</u>

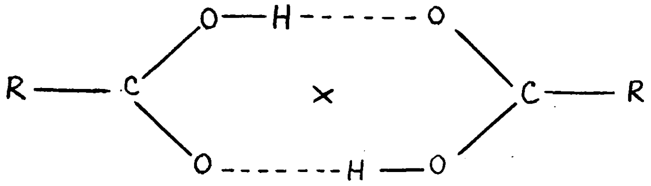
(i) The c-axis of 3.81Å was very short, so it was probable that the molecule of furoic acid would be approximately planar and it was possible that the two molecules in the unit cell would be coplanar.

(ii) Assuming van der Waal's distance to be 3.5Å, the tilt of the molecule to the c-axis was calculated as approximately 24°.

(iii) There was a high refractive index along a direction approximating to that of the $(0\bar{1}1)$ axis, and the angle between this axis and the c-axis was 30°. There was also decided cleavage along this direction. It seemed reasonable, therefore, to assume that the molecules lay in a plane approximately parallel to this axis.

(iv) The intensities of planes (110), (220), (330) etc. were all high.

(v) Conditions were favourable for hydrogen bonding between carboxyl groups of adjacent molecules. In many carboxylic acids, the molecules are arranged in such a way that there is a centre of symmetry between the carboxyl groups, e.g.,



where X̲ is the centre of symmetry. Such an arrangement was possible with the molecules of furoic acid.

c). Calculation of theoretical structure factors.

For a triclinic cell with a centre of symmetry the theoretical structure factor, $F_{calc.}$, for a plane (hko) is given by

$$F_{(hko)} = 2f \sum \cos 2\pi \left({}^{hx}/_{a} + \frac{ky}{b} \right)$$

$^{x}/_{a}$, $^{y}/_{b}$ = atomic coordinates
f = atomic scattering factor.

The values of the atomic scattering factors for carbon and oxygen for each plane were found from data calculated by Cox and Goodwin[24].

For each postulated trial structure, the theoretical structure factors for a number of planes were calculated, and compared with corresponding observed structure factors.

d). Trial Structures.

Consideration of the factors indicating the position of the molecule in the unit cell suggested that the molecule might lie in the (hko) projection in such a way that the atoms made considerable contributions to the (110) plane.

Scale models of the unit cell projection and of the projection of the molecule were made. On the unit cell projection were drawn the projections of the (110), (220), (330), etc. planes. Since the expression for the structure factor is a simple sum of cosines, the structure factors for any position of the molecule in projection could be estimated approximately by inspection.

Good agreement between observed and calculated structure factors was noted when the molecule was placed with the extracyclic carbon to carbon bond lying along the projection of the (220) plane.

3). Refinement by Fourier Synthesis.

a). Fourier syntheses.

The signs of the calculated structure factors were allocated to the corresponding observed structure factors and a two-dimensional Fourier synthesis along the c-axis carried out. The electron density at points (x, y) in the (hko) zone is given by

$$\rho(x,y) = \frac{1}{A}\sum_{-\infty}^{+\infty}\sum_{-\infty}^{+\infty} F_{(hko)} \cos 2\pi\left(\frac{hx}{a} + \frac{ky}{b}\right)$$

The projection along the c-axis was not on to the base of the unit cell but on to a plane perpendicular to the c-axis, i.e., the plane having sides a sin β and b sin α.

For the computation, both axes were divided into sixtieths, $^{a}/_{60}$ = .171Å, $^{b}/_{60}$ = .113Å, and the summation was carried out over one-half of the unit cell, ($\frac{1}{2}$a by b).

The first two Fourier series were calculated using Beevers and Lipson strips[25] which gave two-figure accuracy, but the last two were calculated with three-figure accuracy using Robertson's method[26].

An examination of the electron density map of the second Fourier synthesis showed that the electron densities of peaks representing the ring oxygen and one of the postulated carbon atoms were relatively lower and higher respectively than average. These two atoms were therefore interchanged, and a considerable improvement in the agreement between observed and calculated structure factors resulted.

Calculation of structure factors from coordinates chosen from the fourth Fourier showed that no sign changes occurred. The limit of refinement by this method had therefore been reached.

The electron density map drawn from the final Fourier synthesis is shown in figure 1. The peaks are well resolved, with well-rounded contours of the expected order of magnitude

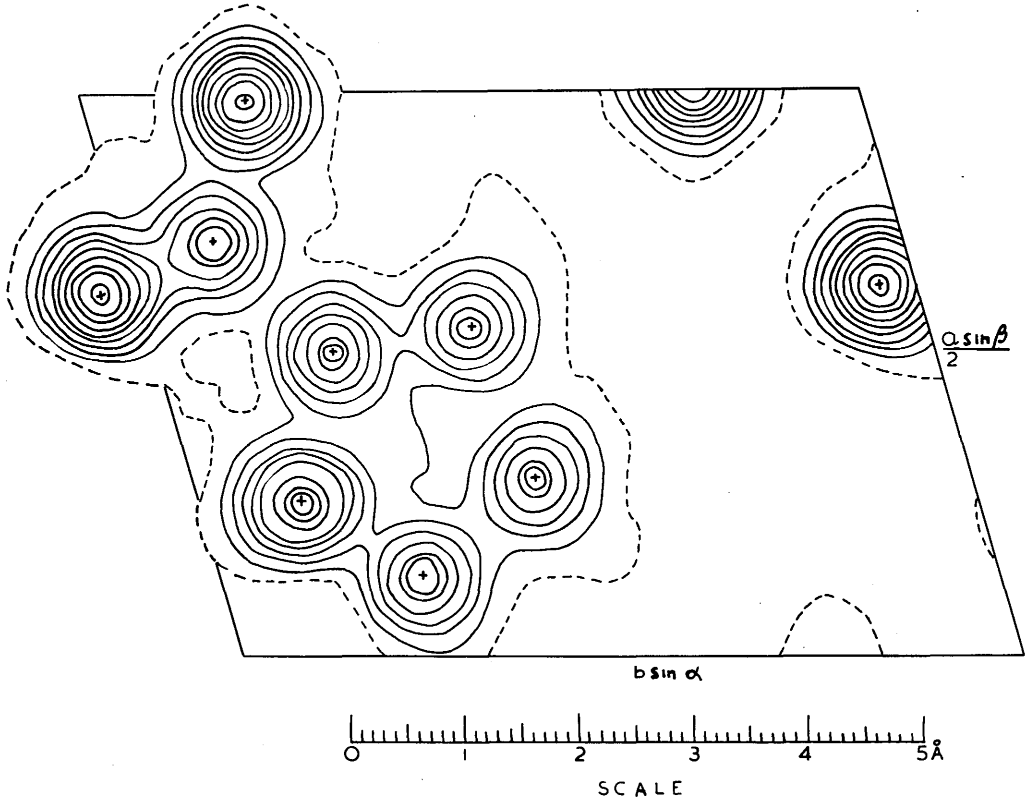


Fig.1. Furoic Acid: Projection along c-axis.

Each contour line represents an electron density increment of one electron per Å^2.
The line representing an electron density of one electron per Å^2 is dotted.

b). Derivation of Experimental Atomic Scattering Curve.

The structure factor for a plane in the (hko) zone in the P$\bar{1}$ space group is given by

$$F_{calc.} = 2 \sum f \cos 2\pi (\frac{hx}{a} + \frac{ky}{b})$$

where f = atomic scattering factor,
$x/_a$, $y/_b$ = atomic coordinates.

If the molecule under consideration is made up of the same atoms, then the atomic scattering factor, f, for any plane (hko) is given by

$$f = \frac{F_{calc.}}{2 \cos 2\pi (hx/_a + ky/_b)}$$

$$= \frac{F_{calc.}}{2S_{(hko)}}$$ where S is the geometrical structure factor.

Since furoic acid contains two different types of atoms in the molecule, it was decided to proceed as follows.

The ratio of electron scattering powers of carbon and oxygen were considered to be 6 to 9 in a compound of this type. The contribution of oxygen to the geometrical structure factor was multiplied by $^9/_6$, and the difference in electron scattering powers of carbon and oxygen thus compensated. The atomic scattering factor, f, for any plane (hko) could then be calculated as before

$$f = \frac{F_{calc.}}{2S_{(hko)}}$$

$$= \frac{F_{obs.}}{2S_{(hko)}}$$ if the structure is correct.

The atomic scattering curve used was the graph of f for any plane against its 2 sin θ value. The graph was placed on an absolute scale by calculating f at 2 sin θ = 0, i.e., for plane (0,0,0)

$$f_{(000)} = \frac{F_{000}}{2S_{000}}$$

$F_{(000)}$ was known accurately, since it was the number of electrons in the unit cell; S_{000} was known since all the atoms made maximum contributions, and the absolute value of $f_{(000)}$ could be calculated.

For furoic acid, $f_{(000)} = 11.42$.

The atomic scattering factors for all planes having $S > 20\%$ of the possible (i.e., S_{000}), were calculated and graphed against the 2 sin θ value for the plane.

Appendix I, Table 11 contains the values for f for various 2 sin θ values.

This atomic scattering curve was used throughout the remainder of the investigation.

4). Final Results (hko) zone.

Structure factors were calculated from coordinates chosen from the final (hko) Fourier and incorporating the experimental atomic scattering curve, for all possible planes in the (hko) zone. The discrepancy, calculated as

$$\frac{\sum\left(|F_{obs}| - |F_{calc}|\right)}{\sum |F_{obs}|}$$

was 12.1%.

A list of observed and calculated structure factors for all planes in the (hko) zone is given in Appendix I, Table 8.

B. Investigation of (hol) zone.

From an inspection of a model of furoic acid it was obvious that resolution in both the (hol) and (okl) projections would be poor. The (hol) zone seemed to offer a slightly better possibility of partial resolution and it was therefore considered first.

1). Observed Structure Factors.

The measurements in this zone were made in exactly the same way as those in the (hko) zone. The intensities of reflections from planes in the (hol) zone were estimated and a list of comparative intensities was made; the range of intensities was approximately 2,000 to 1. 75% of the possible reflections were recorded. These intensities were corrected for Lorentz and polarisation factors, and in addition, were corrected for absorption of X-rays by the crystal. In the case of crystals which are of regular cross-section, absorption effects are not important, but where the cross-section is not uniform, absorption of X-rays has considerable effect. The correction was made as follows:

When a beam of X-rays of intensity I_o is passed through a layer of thickness t, of a crystal whose linear absorption coefficient is μ , then the intensity of the emergent beam, $I_{obs.}$ is given by

$$I_{obs} = I_o e^{-\mu t}$$

For furoic acid, μ = 12.63 cms.$^{-1}$

The path length, t, was measured by finding the direction of the incident and diffracted beams for each plane and graphically measuring the path of the beam through the centre of the crystal for that plane, using a scale model of the crystal and of the reciprocal net.

The observed structure factors were calculated from the corrected intensities.

Scaling was carried out in the first instance by comparison of the observed structure factors of the (hoo) planes in this zone and in the (hko) zone.

2). Trial Structures and Calculation of Theoretical Structure Factors.

a). Space Group.

The (hko) projection was shown to be centrosymmetric, but it was quite feasible that the molecules could be arranged in such a way that there was no centre of symmetry in space, although there was a centre of symmetry in projection, i.e., the confirmation of a centre of symmetry in the (hko) projection did not make space group P_1 impossible. However, calculations were simplified if the centrosymmetric space group $P\bar{1}$ was still assumed.

b). Determination of z-coordinates.

(i) Factors giving some indication of the position of the molecule in the (hol) zone.

The intensities of reflection of X-rays from the crystal gave no assistance in placing the molecule in this zone;

there were only three fairly strong reflections (001), (10$\bar{1}$) and (101), all of them of low 2 sin θ value. The remainder of the sixty-three observed reflections were of low intensity

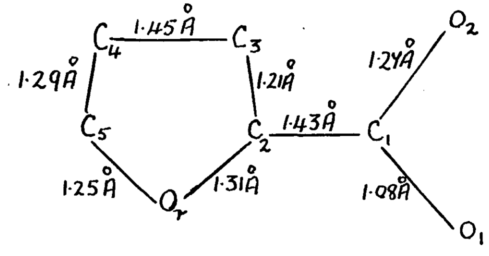
The main indication of the position of the molecule was from a comparison of the dimensions of the molecule in space and in projection. From a knowledge of the bond lengths in projection, and the assumed bond lengths in space, calculations of the z-coordinates were made by the following methods.

(ii). Methods of calculation of the z-coordinates.

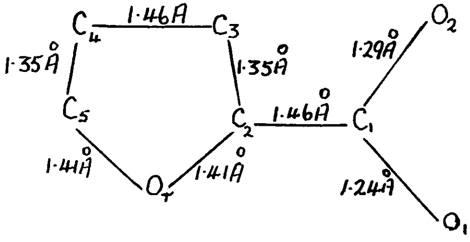
Three main methods of calculation of the z-coordinates were adopted. In all of these methods, the unit cell angles α (= 92°57') and β (= 94°16') were taken as 90°.

Method (A).

From the bond lengths found in projection (I) and as postulated in space (II) the distance along the c-axis of any atom from adjacent atoms could be calculated. To place the molecule in the unit cell, one atom was chosen, and the z-coordinate of this atom was calculated. The z-coordinates of all the other atoms were then calculated since their distances along the c-axis from this atom could be found.



I



II

The carbon atom, C_4, was chosen as the reference atom; the z-coordinate of this atom was calculated with respect to the centre of symmetry between the carboxyl groups as follows: A scale drawing was made of the two molecules in the unit cell linked through this centre of symmetry, and the distance between the reference atom in the two molecules was measured. From the corresponding distance in projection, the z-coordinate of this atom was calculated.

For the molecule to be approximately planar, it was necessary for the following order of z-coordinates of the atoms to be observed.

$$\text{Either}\quad C_3 \leqslant C_4 > C_5 > \mathrm{Or} < C_2 < C_3 \quad \text{and} \quad C_2 > C_1 \left.\right\} \begin{matrix} > O_1 \\ < O_2 \end{matrix}$$

$$\text{Or}\quad C_3 \geqslant C_4 < C_5 < \mathrm{Or} > C_2 > C_3 \quad \text{and} \quad C_2 < C_1 \left.\right\} \begin{matrix} < O_1 \\ > O_2 \end{matrix}$$

The two sets of relationships were the result of the two possible directions of inclination of the molecule to the c-axis.

In this way, two sets of z-coordinates of the atoms were calculated.

Deviations from planarity were possible, but were considered only after the coordinates for an approximately planar structure had been calculated.

In this method, the coordinates of the atoms depended on the postulated dimensions of the molecule. These were assumed from the dimensions found in the case of furan, but the effect of the carboxyl group would probably be sufficient to cause a considerable variation in bond lengths, e.g., the extracyclic carbon to carbon bond could have length between 1.43Å (its length in projection) and 1.54Å. Some decrease in ring bond lengths might be possible, and there was some uncertainty in regard to the dimensions of the carboxyl group. In many initial trial structure analyses, such variations in bond length would be of comparatively small significance, but in the investigation of furoic acid, small movements of the atoms represented a considerable change in atomic coordinates along the short c-axis. This effect was most marked in the case of the reference atom since it represented a movement of the molecule as a whole in the unit cell.

To minimise the effect of this latitude in molecular dimensions, the following method was used for determining the z-coordinate of the reference atom.

For each set of z-coordinates, the values of the structure factors for the three strong planes (001), (101), $(10\bar{1})$ were calculated for values of z-coordinate of the reference atom every $^{1}/18$th along the c-axis, and these values graphed against the corresponding position of the molecule. From this graph, the position of the reference atom which gave good agreement between observed and calculated structure factors was found.

Two sets of atomic coordinates were then calculated as before.

Method (B).

This method depended on the estimation of the inclination of the molecule to the c-axis and involved the assumption that the furan ring at least was planar.

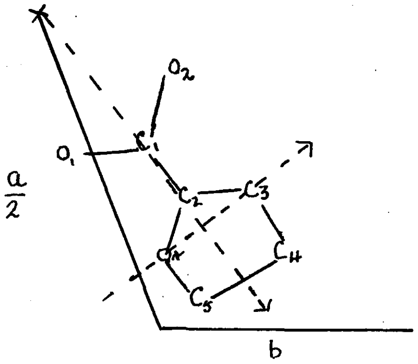
From the discussion of the position of the molecule in the cell (Section A, 2(b)), it was concluded that the molecule lay in a plane parallel to the $(0\bar{1}1)$ axis. Since the shortening of the C_3 to C_4 bond in projection was negligible (1.45Å compared with 1.46Å), it was assumed that the tilt was mainly about this bond as an axis. Scale models of the molecule and of the unit cell were made, and the molecule fitted into the unit cell as decided. The distance along the c-axis of each atom with respect to the reference atom, C_4, was then measured. In this method, too, the positions of all the atoms depended on the molecular dimensions postulated, and the z-coordinate of the reference atom, C_4, was determined as in method (A).

Method (C).

This method required the assumption that the molecule of furoic acid was planar, and that the two molecules linked by hydrogen bonds were coplanar. It required, however, the postulation of only one dimension: the C_4 to C_5 bond was taken as 1.35Å, as postulated before.

The method has already been described in the investigation of the structure of coronene[27].

Arbitrary orthogonal molecular axes L and M in the plane of the (hko) projection (see fig.   ) and N perpendicular to this plane were chosen.



The crystal axes were assumed to be monoclinic, and their direction cosines with respect to these orthogonal axes were calculated. The molecular coordinates with respect to these orthogonal axes were then found, and from these values, the z-coordinates of the atoms were determined.

The fact that this method required the assumption that the two molecules of furoic acid were planar made it unsatisfactory; method (B), in which the ring must be assumed planar seemed more reasonable, since all the evidence indicated that this was so in the parent compound, furan, while method (A) required no assumption of planarity. The methods were therefore investigated in the following order, (A), (B), (C) by the usual method of comparison of theoretical and observed structure factors.

b). <u>Calculation of Theoretical Structure Factors.</u>

The structure factor, $F_{calc.}$ for a plane (hol) is given by

$$F_{calc.} = 2 \sum f \cos 2\pi \left({}^{hx}/_{a} + {}^{lz}/_{c} \right)$$

The x-coordinates were those estimated from the final (hko) Fourier synthesis; the atomic scattering factors were found from the experimental atomic scattering curve.

c). Trial Structures.

Method (A).

Structure factors calculated using z-coordinates obtained by this method showed poor agreement with observed structure factors. Many attempts were made to refine these coordinates by consideration of the variations possible in each of the bond lengths, of planar and non-planar structures, but the structures giving best agreement between observed and calculated structure factors showed discrepancies of 35% and 38% calculated as

$$\frac{\sum \left(|F_{obs}| - |F_{calc}| \right)}{\sum |F_{obs}|}$$

Attempts to refine these structures by two-dimensional Fourier syntheses were unsuccessful, and the structures therefore were considered incorrect.

Consideration of the number of possible variations in a structure such as this showed that there was an almost infinite number of combinations of such factors. An investigation was made of literally more than a thousand trial structures without success, and a few examples of the methods employed are given in Appendix II.

Method (B).

z-coordinates calculated by this method gave structure factors which showed poor agreement with observed structure factors. Attempts were made to obtain modifications in which the agreement was improved by the same methods as used in the investigations by method (A), but without success.

Method (C).

Since investigations of the structure of furoic acid by methods (A) and (B) had proved unsuccessful, method (C) was applied.

Structure factors calculated from z-coordinates obtained by this method showed poor agreement with observed structure factors.

The z-coordinates of the atoms obtained by this method, however, showed two significant differences from those obtained by the two previous methods, indicating the following changes in z-coordinates:

(i) a movement of the whole molecule along the c-axis towards the origin by approximately $\frac{c}{6}$,

(ii) a decrease in z-coordinate of the ring oxygen relative to the adjacent atoms.

Using the method by which the successful trial structure was obtained in the (hko) zone, a set of coordinates was found, after some attempts, which gave rough qualitative agreement between observed and calculated structure factors. Structure factors calculated for all planes in the (hol) zone showed a discrepancy of 27.6%. It was decided, therefore, to carry out a Fourier synthesis applying the signs of these structure factors to the observed structure factors.

3). Refinement by Fourier Synthesis.

A Fourier synthesis was carried out, projecting down the b-axis on to a plane perpendicular to the b-axis having sides a sin γ and c sin α

For the computation, the a-axis was divided into sixtieths, $a/60$ = .171Å and the c-axis into thirtieths, $c/30$ = .127Å. The summation was carried out over one-half of the unit cell ($\frac{1}{2}$a by c) by means of Robertson's strips[26] which give three-figure accuracy. The resolution in the Fourier map (fig.2) was not very good, and so the determination of atomic centres was rather uncertain.

Structure factors calculated from coordinates estimated from the (hol) projection showed a sign change in only one plane, and its value was very small. Since the resolution was poor, it was decided that the limit of refinement by two-dimensional Fourier analysis had been reached.

4). Final Results (hol) zone.

A list of calculated and observed structure factors for all planes in the (hol) zone is given in Appendix I, Table 9. The discrepancy, expressed as

$$\frac{\sum \left(|F_{obs}| - |F_{calc}| \right)}{\sum |F_{obs}|}$$

was calculated as 16.9%.

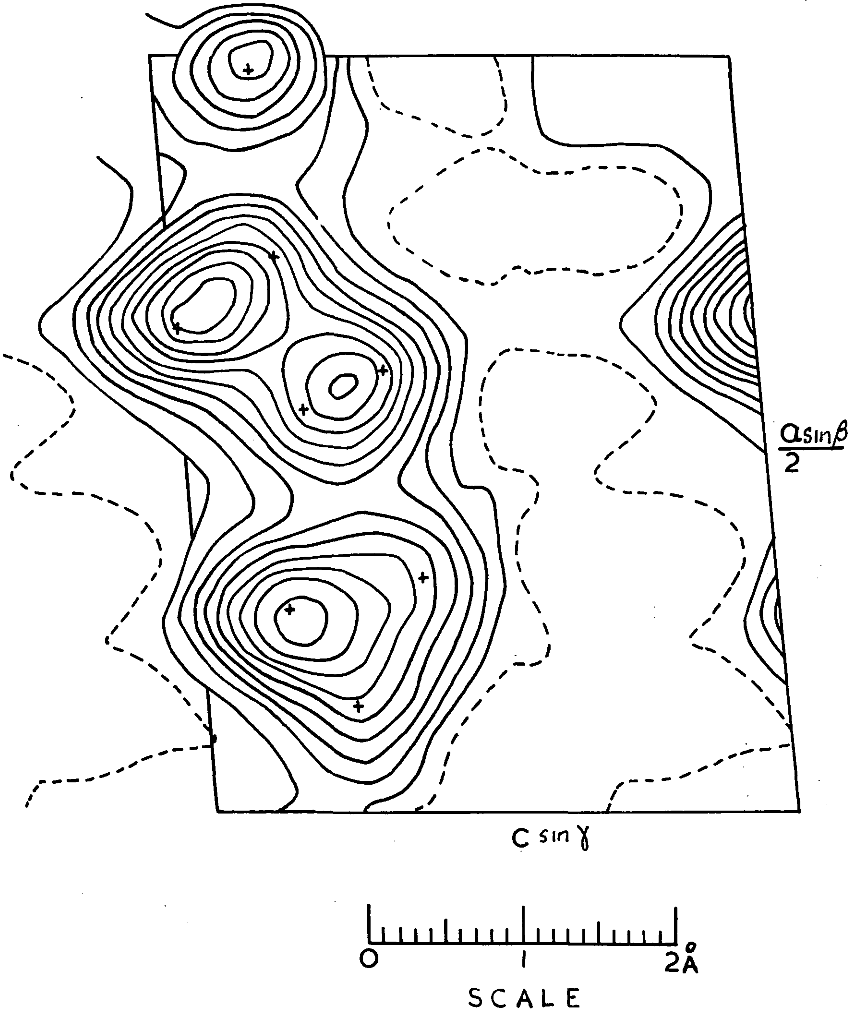


Fig.2. Furoic Acid: Projection along b-axis.

Each contour line represents an electron density increment of one electron per $Å^2$.

The line representing an electron density of one electron per $Å^2$ is dotted.

C. Investigation of (okl) zone.

Since the resolution obtainable in this projection would be even less than in the (hol) projection, it was decided that no useful information would be obtained from a Fourier synthesis, and so only a comparison of theoretical and observed structure factors was made.

1). Observed Structure Factors.

The measurements in this zone were made in exactly the same way as those in the (hko) and (hol) zones. The intensities of reflections of the planes in the (okl) zone were estimated and a list of comparative intensities made; the range of intensities was approximately 2,000 to 1. 64% of the possible reflections were recorded. From corrected intensities, the observed structure factors were calculated.

These comparative structure factors were scaled by comparison with the calculated structure factors.

2). Theoretical Structure Factors.

The structure factor for a plane (okl) in the (okl) zone is given by

$$F_{calc} = \sum 2f \cos\left(\frac{ky}{b} + \frac{lz}{c}\right) 2\pi$$

From the y- and z-coordinates obtained from the (hko) and (hol) projections, the structure factors for all planes in the (okl) zone were calculated.

3). Final Results.

A list of calculated and observed structure factors for all planes in the (okl) zone is given in Appendix I, Table 10.

The discrepancy, expressed as

$$\frac{\sum\left(|F_{obs}| - |F_{calc}|\right)}{\sum|F_{obs}|}$$

was calculated as 12.8%.

Coordinates and Dimensions of the Molecule.

Coordinates of the atoms determined from the (hko) and (okl) Fourier syntheses as fractions of unit cell axes were expressed in Angstrom units; these were thus the coordinates referred to the triclinic crystal axes, and are given in Table 1.

For the calculation of the dimensions of the molecule these triclinic coordinates were referred to orthogonal axes as follows. An appropriate choice of orthogonal axes simplified the calculation; those chosen were the crystal c-axis, the projection of the a-axis on the plane perpendicular to the c-axis, i.e., a sin β (compare fig. 1.) and an axis at right angles to a sin β and to c. The orientation of the triclinic crystal axes to these axes was then found by calculation of χa, ψa, ωa, χb, ψb, ωb; and χc, ψc, ωc, the angles which the <u>a</u>, <u>b</u> and <u>c</u> triclinic crystal axes made with the orthogonal <u>x</u>, <u>y</u> and <u>z</u> axes respectively. These values are listed in Table 2.

Then, from the triclinic crystal coordinates of each atom, x, y and z, the orthogonal co-ordinates could be calculated as follows:

$$x' = x \cos \chi a + y \cos \chi b + z \cos \chi c.$$

$$y' = x \cos \psi a + y \cos \psi b + z \cos \psi c.$$

$$z' = x \cos \omega a + y \cos \omega b + z \cos \omega c.$$

The orthogonal coordinates of the atoms are listed in Table 3.

Table 1. Triclinic Crystal Coordinates.

Atom	$360\frac{x}{a}$	$360\frac{y}{b}$	$360\frac{z}{c}$	xÅ	yÅ	zÅ
C_1	132.0	40.8	66.0	3.755	0.770	0.699
C_2	96.3	102.2	73.2	2.740	1.552	0.775
C_3	84.7	149.1	124.8	2.979	2.816	1.321
C_4	56.1	158.4	139.2	1.596	2.991	1.473
C_5	25.5	93.0	91.2	0.726	1.756	0.965
O_r	49.2	47.4	54.0	1.400	0.895	0.572
O_1	116.1	-17.7	2.0	3.303	-0.334	0.025
O_2	177.0	75.0	61.2	5.036	1.416	0.648

Table 2. Orientation of Triclinic Axes.

$\chi a = \beta - 90^\circ = 4^\circ 16'$ $\quad \chi b = 106^\circ 26'$ $\quad \chi c = 90^\circ$

$\psi a = 90^\circ$ $\quad \psi b = 16^\circ 43'$ $\quad \psi c = 90^\circ$

$\omega a = \beta = 94^\circ 16'$ $\quad \omega b = \alpha = 92^\circ 57'$ $\quad \omega c = 0^\circ$

Table 3. Orthogonal Coordinates.

Atom	x'Å	y'Å	z'Å
C_1	3.527	0.738	0.380
C_2	2.293	1.486	0.491
C_3	2.174	2.697	0.955
C_4	0.745	2.865	1.201
C_5	0.227	1.682	0.821
O_r	1.143	0.857	0.421
O_1	3.388	-0.320	-0.203
O_2	4.621	1.356	0.200

From the orthogonal coordinates, the bond lengths in the molecule were calculated. These are listed in Table 4.

The distances between atoms in different molecules were also calculated; the relationship between adjacent molecules is shown in fig.3. Those intramolecular distances less than 4.5Å are listed in Table 5.

Values of the angles between the bonds are noted in Table 6.

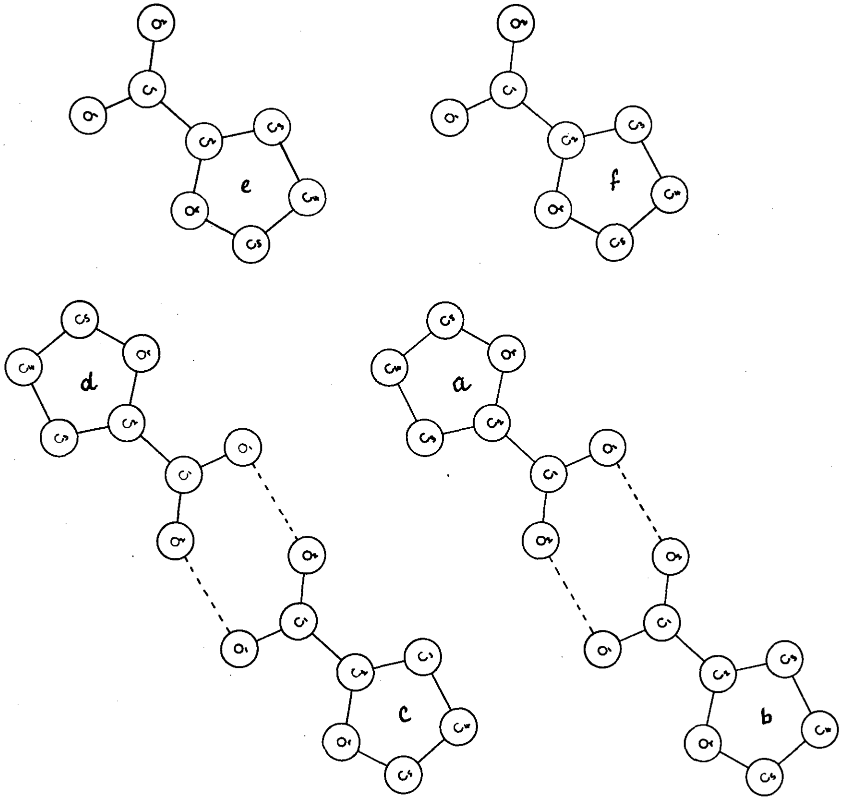


Fig.3. Furoic Acid. Relative Positions of the Molecules.

Table 4. Bond Lengths.

Bonds	Length Å
C_2C_3	1.30
C_3C_4	1.46
C_4C_5	1.35
C_5O_r	1.30
O_rC_2	1.31
C_2C_1	1.45
C_1O_1	1.22
C_1O_2	1.27
O_1O_2	2.12

Table 5. Intermolecular Distances.

	Length Å
$O_{2a}O_{1b}$	2.55
$O_{1a}O_{2b}$	2.55
$O_{2a}O_{2c}$	4.20
$C_{4a}C_{5e}$	4.23
$C_{4a}C_{4e}$	4.45
$O_{ra}C_{5f}$	3.14
$C_{5a}C_{5f}$	3.77

Table 6. Bond Angles

$C_5\hat{C}_4C_3$	103.2°
$C_4\hat{C}_3C_2$	104.9°
$C_3\hat{C}_2O_r$	112.6°
$C_2\hat{O}_rC_5$	107.4°
$O_rC_5C_4$	111.9°
$O_r\hat{C}_2C_1$	119.7°
$C_3\hat{C}_2C_1$	125.9°
$C_2\hat{C}_1O_1$	113.0°
$C_2\hat{C}_1O_2$	119.7°
$O_1\hat{C}_1O_2$	117.0°

Accuracy of Results.

Investigations of the accuracy of atomic coordinates in recent years[28] showed that the greatest errors were introduced by finite termination of Fourier series. In this present investigation, no correction was made for this factor, and this, together with the poor resolution obtained in the (hol) zone, suggested that the error in the bond lengths of furoic acid determined in this analysis was probably of the order of ±.04Å.

Conclusions.

The conclusions which may be drawn from the results of this investigation are as follows:-

(1) The bonds in the furan ring show a considerable decrease in length from corresponding single bond lengths.

(2) The extracyclic carbon to carbon bond is significantly shorter than the carbon to carbon single bond. This is presumably due to resonance between the carboxyl group and the ring.

(3) There is hydrogen bonding between the carboxyl groups of adjacent molecules.

(4) The atoms forming the furan ring lie to within ±.03Å in a plane whose equation referred to orthogonal axes is

$$.228x - .671y + 1.777z - .382 = 0$$

The atoms of the carboxyl group lie away from this plane, C_1 by .314Å, O_1 by .127Å, and O_2 by .061Å.

(5) The equation of the plane of the carboxyl group referred to orthogonal axes is

$$.550x - .663y + 1.072z - 1.857 = 0$$

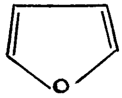
This plane makes an angle of 20° with the plane of the furan ring.

Discussion.

I. Bond Lengths.

The dimensions of the furan ring found in this investigation of furoic acid indicate considerable shortening of all the bond lengths from those of single bonds.

In furan itself, similar decreases in bond lengths in the ring were noted in electron diffraction investigations and Pauling and Schomaker[10] suggested that the explanation might be found in the presence of an unshared electron pair on the oxygen atom. From the heat of hydrogenation of furan, the resonance energy was calculated by them as 23K/cal. per mole., and this could be accounted formeither by the canonical structures of a conjugated diene (I)nor by structures analogous to those in divinyl ether (II) which lead to a resonance energy of only 3.4K cal/mole.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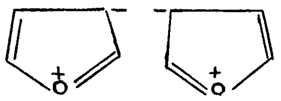
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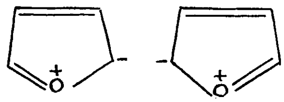

III

On the other hand, structures of type III have no close analogues in either a conjugated diene or in divinyl ether; they are relatively stable since the formal charges are not widely separated. They are, therefore, probably responsible for a large part of the comparatively large resonance energy of furan. Pauling and Schomaker[10], from a consideration of the lengths of the ring oxygen bonds, calculated that the contribution of these structures was about 8%. However, they pointed out that a consideration of dipole moments gives a different figure.

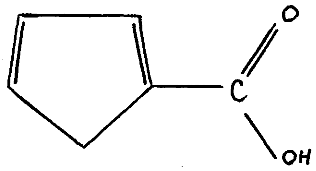
The dipole moment of furan in benzene solution is 0.67D, whereas that of tetrahydrofuran is 1.68D. This difference in moment is due, in part, to the change of C-H moments combined with a resonance moment in the same direction of about .95D, the effect of changing the angles in the ring being neglected. This resonance moment corresponds to total contributions from charged structures of about 15%. The figure calculated from bond lengths was thus rather less than expected.

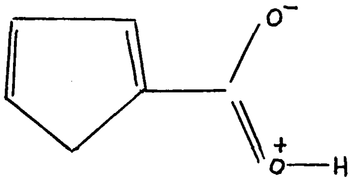
From a comparison of the bond lengths in the ring found in the present investigation and those found from electron diffraction[10,11] (Table 7), it is evident that the resonance in furoic acid is very much greater.

Table 7. Comparison of Ring Bond Lengths in Furan and Furoic Acid.

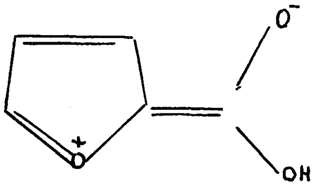
Bond	Length Å in Furoic Acid	Length Å in Furan
C_2C_3	1.30	1.35
C_3C_4	1.46	1.46
C_4C_5	1.35	1.35
C_5O_r	1.30	1.41
O_rC_2	1.31	1.41

This was to be expected in view of the greater chemical stability of furoic acid, and its more definite aromatic character. The carboxyl group has a stabilising effect corresponding to a resonance energy of 28K cal/mole for acids due to resonance between structures such as

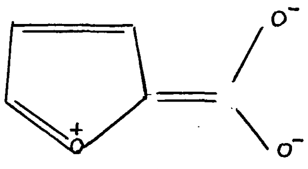




In furoic acid there must be some considerable resonance between the ring and the carboxyl group, as well as between the members of these groups themselves. The length of the extra cyclic carbon to carbon bond, 1.45Å, represents a bond having 20% double bond character; this was calculated from formulae given by Pauling[29] and Wheland[30]. There must, therefore, be contributions from structures of the type A and B

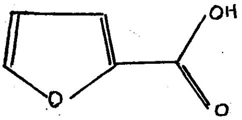


A

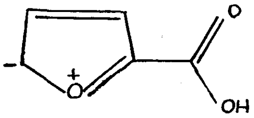


B

The considerable decrease in length of the bonds C_2O_r, C_5O_r and the slight shortening of C_2C_3 in furoic acid compared with the values found from furan, indicate contributions from structures of the type C - G.



C



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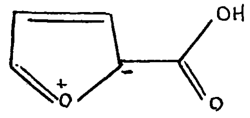
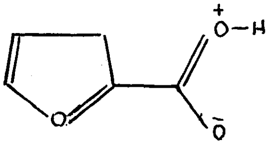


E



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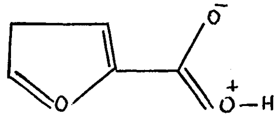


G

The nuclear resonance in this compound thus enhances the resonance of the carboxyl group, resulting in greater stabilisation and increase in resonance energy.

II. Intermolecular Distances.

The molecule is further stabilised by strong hydrogen bonding between the carboxyl groups of neighbouring molecules. The value of bond length, 2.55Å, is closer to the value found in the acid salt of p-hydroxy benzoic acid[31] than to that found in aliphatic acids[20-23], and this type of arrangement in which two carboxyl groups are linked across a centre of symmetry by hydrogen bonds is very common[20-23]. In a few cases, the hydrogen bond is required to be symmetrical because of space group considerations[31], but this is rare and in furoic acid, the hydrogen bond need not be symmetrical.

The only other intermolecular length which appears to be anomalous, is the distance between O_{ra} and C_{5f}, viz., 3.14Å. The van der Waal's radius for oxygen is about 1.40Å, and for carbon in an aromatic molecule about 1.85Å, giving a van der Waal's contact distance of approximately 3.25Å. The deviation is not great in view of the uncertainty of the van der Waal's values. The shortening may be due to an attraction of the oxygen with positive formal charge to the carbon C_5 which may be written with a negative charge in some structures such as E. This latter fact is substantiated by the fact that bromination of furoic acid gives 5-bromofuroic acid.

From a study of the intermolecular distances, it can be seen that the structure is very loosely linked; only two distances less than 4.0Å are recorded. Two molecules are linked to each other by hydrogen bonds, and these form the repeating unit of a layer structure. This would explain the very pronounced cleavage, and the high birefringence moted in furoic acid. These values differ considerably from the dimensions of the furanose ring found in sucrose sodium bromide dihydrate, in which some unusual bond lengths were noted. Some decrease in the bond lengths from single bond lengths were found, but it is interesting to note that in this molecule, the lengths of the formal double bonds are considerably greater than observed in the electron diffraction investigation of furan itself (1.44 compared with 1.35), suggesting that there is, in fact, suppression of even normal resonance to some extent.

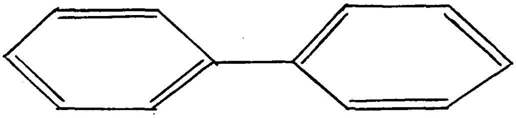
III. Bond Angles.

The bond angles in the furan ring in furoic acid (Table 6) are slightly different from the tetrahedral angle, as is to be expected from the shortening of the bonds. They agree fairly well with the values found from electron diffraction investigations. In the carboxyl group, the angle $O_1\hat{C}_1O_2$ is rather less than usually reported[20-23]. This distortion may be due to the fact that the carboxyl group is not in the plane of the ring.

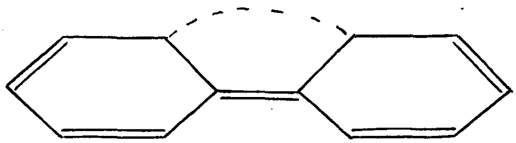
IV. Planarity.

It has been found that the furan ring and the carboxyl group are not coplanar but lie in two planes inclined to each other at 20°. Probably, the best idea of the relation of the carboxyl group to the ring is given by the inclination of the extracyclic carbon to carbon bond. This bond makes an angle of 12.5° with the ring.

A compound such as furoic acid, where there is conjugation between two resonating systems (viz. the furan ring and the carboxyl group), may be compared with diphenyl. This compound,



is stabilised not only by resonance in the benzene rings, but also to a small extent by conjugation between the rings due to contribution from structures such as



The resonance is greatest when the molecule is planar, and, therefore, this is the expected configuration. The same effect should occur with a carboxyl group. In furoic acid, however, the carboxyl group is not in the plane of the ring. Several factors may contribute toward the slight deviation from planarity. Firstly, the ring is not entirely aromatic in nature, and bond angles of 120° would cause considerable strain in the molecule. Secondly, steric effects may cause distortion of the carboxyl group. Thirdly, there may be some attraction between the positively charged oxygen atom of the ring and the corresponding negatively charged oxygen of the carboxyl group: this would cause buckling of the structure, forcing the extracyclic carbon to carbon bond out of the plane of the ring. It is interesting to note that the carbon of the carboxyl group is furthest out of the plane of the ring with the two oxygen atoms as nearly in the plane as possible: one, indeed, is only .06Å out of the plane.

In sucrose sodium bromide dihydrate[1] the furan ring shows some unexpected features. Four of the ring members, including the oxygen atom, are in one plane, with the fifth atom away from this plane by about 0.5Å. In this case, the departure from planarity of the ring effects a more general planarity of the molecule, even though this involves some degree of distortion from the tetrahedral angle: the average bond angle is 104°.

This discussion has been purely qualitative. A molecular orbital treatment such as has been carried out in the case of the five-membered heterocyclic thiophene[32] should yield interesting results from a theoretical point of view. Such a semi-quantitative treatment would give more definite evidence of the reason for the bond lengths established by this investigation.

Appendix I.

Tables of Calculated and Observed Structure Factors.

Table 8. Observed and Calculated Structure Factors (hk0) Zone.

(hk0)	2 sin θ	$F_{obs.}$	$F_{calc.}$	(hko)	2 sin θ	$F_{obs.}$	$F_{calc.}$
100	.156	9.0	-8.2	520	1.016	7.6	7.0
010	.236	17.1	19.1	610	1.029	10.4	9.2
$1\bar{1}0$	.242	21.4	20.6	$5\bar{4}0$	1.044	<1.0	-1.2
200	.312	12.8	-13.0	$7\bar{1}0$	1.056	7.1	-6.6
110	.316	43.1	-42.5	$7\bar{2}0$	1.066	<1.0	0.3
$2\bar{1}0$	.335	14.4	14.6	430	1.067	7.9	7.4
210	.440	8.9	-9.3	240	1.074	<1.0	1.4
$1\bar{2}0$	.452	<0.6	-0.2	700	1.092	1.7	1.5
$3\bar{1}0$	.465	17.2	17.9	$6\bar{4}0$	1.122	4.2	4.9
300	.468	<0.6	1.7	$7\bar{3}0$	1.123	3.6	-3.0
020	.472	4.6	6.9	$2\bar{5}0$	1.131	3.6	4.8
$2\bar{2}0$	.485	12.7	-12.8	$3\bar{5}0$	1.139	3.7	-3.8
120	.536	1.0	1.0	$1\bar{5}0$	1.144	4.8	-4.6
$3\bar{2}0$	.560	26.1	25.5	340	1.161	3.3	-2.1
310	.581	1.8	0.4	620	1.165	2.9	3.5
$4\bar{1}0$	.605	3.1	-4.8	$4\bar{5}0$	1.169	8.8	8.5
400	.624	4.9	-5.3	050	1.180	1.8	2.6
220	.632	21.5	-20.7	710	1.187	<1.0	-1.6
$4\bar{2}0$	.670	23.4	-23.6	530	1.192	8.5	8.3
$1\bar{3}0$	.674	4.4	4.6	$8\bar{2}0$	1.212	6.3	-6.2
$2\bar{3}0$	.681	2.5	0.6	$8\bar{1}0$	1.214	5.4	4.9
030	.708	14.0	-14.2	$5\bar{5}0$	1.218	2.9	1.4
$3\bar{3}0$	.726	14.2	18.6	150	1.232	1.3	-3.2
410	.730	10.8	-11.1	$7\bar{4}0$	1.234	8.3	-8.9
320	.749	1.8	0	800	1.248	3.2	3.0
$5\bar{1}0$	.751	3.2	-1.9	$8\bar{3}0$	1.253	3.2	-1.8
130	.762	<0.8	-2.1	440	1.270	8.8	8.1
500	.780	23.1	-23.5	$6\bar{5}0$	1.287	1.9	2.2
$4\bar{3}0$	.797	7.1	-8.9	250	1.300	3.2	-2.9
230	.850	9.5	-8.2	720	1.309	8.6	7.8
510	.878	6.1	-5.9	630	1.322	<1.1	-1.0
420	.880	5.3	-4.4	$8\bar{4}0$	1.340	5.7	-5.3
$5\bar{2}0$	.890	<0.9	1.5	810	1.342	<1.1	-0.4
$5\bar{3}0$	.892	9.5	-11.2	$2\bar{6}0$	1.348	1.9	1.2
$2\bar{4}0$	.904	7.0	5.8	$3\bar{6}0$	1.355	5.8	-5.8
$6\bar{1}0$	.905	<0.9	0.1	$9\bar{2}0$	1.357	11.4	10.2
$1\bar{4}0$	.910	13.9	-14.6	$9\bar{1}0$	1.365	7.0	6.6
$3\bar{4}0$	.926	6.3	5.6	$7\bar{5}0$	1.372	<1.1	0.4
$6\bar{2}0$	.930	7.8	10.9	$4\bar{6}0$	1.372	1.5	-1.9
600	.936	12.7	10.9	$1\bar{6}0$	1.376	4.8	-4.9
040	.944	<0.9	0.6	350	1.379	<1.1	-0.8
330	.950	7.0	8.7	$9\bar{3}0$	1.386	7.0	6.6
$4\bar{4}0$	.965	7.4	7.8	540	1.389	2.9	-3.9
140	.998	9.5	10.0	900	1.404	4.1	-4.5
$6\bar{3}0$	1.004	4.8	-5.4	$5\bar{6}0$	1.405	9.1	9.6

(hko)	2 sin θ	$F_{obs.}$	$F_{calc.}$
060	1.416	5.2	-5.6
$6\bar{6}0$	1.452	<1.1	0.8
$9\bar{4}0$	1.460	2.3	-1.8
$8\bar{5}0$	1.462	2.3	2.1
730	1.468	1.3	0.5
820	1.470	1.3	-1.9
160	1.470	3.0	3.6
450	1.480	6.2	5.3
910	1.495	<1.1	-0.3
$10,\bar{2}0$	1.504	<1.1	-1.1
640	1.510	6.1	-5.2
$10,\bar{1}0$	1.525	4.7	-4.3
$10,\bar{3}0$	1.525	1.8	1.3
$7\bar{6}0$	1.526	2.3	-1.6
260	1.538	2.3	2.5
10,00	1.560	<1.1	-0.8
$9\bar{5}0$	1.560	3.2	-3.2
550	1.584	6.1	-5.9
$10,\bar{4}0$	1.585	1.5	0.4
$3\bar{7}0$	1.588	<1.1	-1.2
$2\bar{7}0$	1.593	<1.0	0.2
$4\bar{7}0$	1.595	6.6	-7.1
$8\bar{6}0$	1.698	0.7	0.8
920	1.607	<1.0	-1.0
830	1.610	5.2	-6.1
360	1.613	<1.0	0.4
$1\bar{7}0$	1.616	<1.0	-0.3
$5\bar{7}0$	1.616	2.5	1.6
740	1.635	<1.0	0.1
070	1.652	<1.0	0.5
10,1,0	1.652	2.8	2.5
$6\bar{7}0$	1.656	<1.0	0
$11,\bar{2},0$	1.661	<1.0	-0.2
$10,\bar{5},0$	1.674	1.7	-1.6
$11,\bar{1},0$	1.679	1.4	-1.8
$9\bar{6}0$	1.690	1.7	1.3
460	1.700	<1.0	0.4
650	1.700	<1.0	0.5
170	1.708	4.8	5.3
$7\bar{7}0$	1.708	1.7	2.4
11,00	1.716	1.4	-1.5
$11,\bar{3}0$	1.721	1.1	0.5
$11,\bar{4},0$	1.726	< 0.9	0.2
930	1.753	< 0.9	0.1
10,2,0	1.755	< 0.9	-0.1
$8\bar{7}0$	1.771	< 0.9	-0.1
840	1.772	< 0.9	-0.4
270	1.773	0.9	-1.6
$10,\bar{6},0$	1.787	1.2	-1.4

(hko)	2 sin θ	$F_{obs.}$	$F_{calc.}$
560	1.801	1.4	-1.8
$11,\bar{5},0$	1.805	0.9	-1.1
$4\bar{8}0$	1.808	1.3	-1.1
11,10	1.814	1.1	-1.0
$12,\bar{2},0$	1.814	<0.8	-0.4
$2\bar{8}0$	1.815	1.3	1.3
$3\bar{8}0$	1.815	<0.8	0.3
$12,\bar{3},0$	1.816	1.1	0.7
750	1.822	<0.8	0.8
$5\bar{8}0$	1.829	<0.8	0.7
$12,\bar{1},0$	1.835	<0.8	-0.5
970	1.844	<0.8	0.1
370	1.846	<0.8	-0.2
$1\bar{8}0$	1.854	<0.8	0.6
$12,\bar{4},0$	1.857	3.2	1.2
$6\bar{8}0$	1.860	1.2	-2.0
12,0,0	1.872	<0.7	0.6
080	1.888	<0.7	0.2
10,3,0	1.896	<0.7	0.4
$7\bar{8}0$	1.902	<0.7	-0.5
$11,\bar{6},0$	1.903	<0.7	0.3
940	1.907	<0.7	-0.5
660	1.910	<0.7	0.2
11,2,0	1.915	<0.7	-0.9
$12,\bar{5},0$	1.921	0.9	1.5
470	1.927	<0.6	-0.3
$10,\bar{7},0$	1.929	<0.6	-0.3
$8\bar{8}0$	1.934	<0.4	1.8
180	1.945	<0.4	1.6
850	1.946	<0.4	-0.9
$13,\bar{2},0$	1.957	<0.4	0.2
$13,\bar{3},0$	1.959	<0.4	-0.8

Table 9. Observed and Calculated Structure Factors - (hol) Zone.

(hol)	2 sin θ	$F_{obs.}$	$F_{calc.}$	(hol)	2 sin θ	$F_{obs.}$	$F_{calc.}$
001	.406	25.9	26.3	802	1.528	1.1	-1.2
$10\bar{1}$	.429	25.2	25.6	603	1.574	<0.9	1.6
101	.442	49.6	-50.3	$90\bar{2}$	1.598	5.6	6.7
$20\bar{1}$	.502	8.7	7.3	$70\bar{3}$	1.603	1.7	2.6
201	.525	7.5	-5.9	$10,0,\bar{1}$	1.604	3.2	-2.8
$30\bar{1}$	.608	12.8	12.9	004	1.625	<0.8	-0.8
301	.636	1.8	-1.6	$10\bar{4}$	1.625	<0.8	-1.9
$40\bar{1}$	.732	2.7	4.9	104	1.640	<0.8	1.3
401	.764	8.9	-8.5	10,0,1	1.641	3.1	2.6
002	.813	11.6	-12.0	$20\bar{4}$	1.641	<0.8	-0.3
$10\bar{2}$	.820	1.3	1.2	902	1.663	1.0	0.5
102	.835	4.8	-4.4	204	1.670	<0.8	0.1
$20\bar{2}$	.857	4.7	-5.8	$30\bar{4}$	1.670	<0.8	2.4
$50\bar{1}$	.868	9.3	-9.3	703	1.679	1.7	0.4
202	.886	3.1	-4.7	$80\bar{3}$	1.710	4.9	-3.5
501	.901	4.0	-5.2	304	1.712	0.7	-0.9
$30\bar{2}$	.920	9.3	9.9	$40\bar{4}$	1.714	2.0	1.3
302	.958	1.8	-0.2	$10,0\bar{2}$	1.735	<0.9	0.5
$40\bar{2}$	1.004	5.4	-4.5	$11,0\bar{1}$	1.757	1.5	-1.7
$60\bar{1}$	1.009	2.3	-0.6	404	1.769	1.5	-0.2
601	1.043	11.3	10.7	$50\bar{4}$	1.772	1.4	-2.0
402	1.050	4.5	-1.8	803	1.791	2.7	-4.2
$50\bar{2}$	1.104	2.7	0.9	11,0,1	1.793	1.3	-1.2
$70\bar{1}$	1.154	4.7	-3.8	10,0,2	1.802	<0.8	0.1
502	1.155	4.8	3.4	$60\bar{4}$	1.816	<0.7	-0.9
701	1.191	1.4	-2.1	$90\bar{3}$	1.823	1.2	1.7
$60\bar{2}$	1.216	4.3	4.0	504	1.837	<0.7	-0.7
003	1.219	1.7	-3.5	604	1.840	<0.7	-1.2
$10\bar{3}$	1.222	1.6	-2.3	$11,0,\bar{2}$	1.875	<0.7	-0.7
103	1.236	1.6	1.3	903	1.909	<0.5	1.3
$20\bar{3}$	1.245	4.6	-4.6	$12,0,\bar{1}$	1.910	<0.5	-0.3
203	1.273	3.1	-4.7	$70\bar{4}$	1.920	<0.5	-0.9
602	1.273	1.8	3.4	11,0,2	1.943	<0.5	-1.4
$30\bar{3}$	1.286	4.6	5.2	12,0,1	1.946	<0.5	1.0
$80\bar{1}$	1.303	5.7	4.2				
303	1.327	1.8	6.1				
$70\bar{2}$	1.337	3.4	-1.7				
801	1.339	1.8	-1.4				
$40\bar{3}$	1.345	2.1	-2.9				
403	1.396	1.7	2.2				
702	1.397	2.0	3.5				
$50\bar{3}$	1.419	3.7	-3.4				
$90\bar{1}$	1.453	5.3	4.9				
$80\bar{2}$	1.464	5.6	-4.9				
503	1.480	2.7	3.5				
901	1.489	2.3	-1.0				
$60\bar{3}$	1.506	1.8	-0.9				

Table 10. Observed and Calculated Structure Factors -(okl) Zone.

(okl)	2 sin θ	$F._{obs.}$	$F_{calc.}$	(okl)	2 sin θ	$F_{obs.}$	$F_{calc.}$
$0\bar{1}1$	.454	75.3	76.9	024	1.726	<1.6	2.0
011	.485	17.1	-12.8	071	1.732	<1.6	0.7
$0\bar{2}1$	.599	8.8	8.4	053	1.760	2.7	0.6
021	.645	13.9	-14.9	$0\bar{7}2$	1.786	<1.6	-1.1
$0\bar{3}1$	.790	< 1.4	-0.9	$0\bar{6}3$	1.797	<1.6	-1.4
$0\bar{1}2$	.829	13.3	12.7	034	1.801	<1.6	1.4
031	.843	3.3	-2.2	$0\bar{4}4$	1.816	<1.4	2.9
012	.863	5.7	-8.5	072	1.895	<1.2	0.5
$0\bar{2}2$	.908	30.4	31.9	$0\bar{8}1$	1.902	<1.2	-0.2
022	.970	3.5	3.0	$0\bar{5}4$	1.917	<1.0	-0.5
$0\bar{4}1$	1.000	10.8	-9.5	063	1.935	<1.0	0
$0\bar{3}2$	1.037	2.0	1.5	044	1.940	1.6	1.2
041	1.055	9.2	8.5	081	1.962	< 0.8	0.8
032	1.117	11.6	10.6	$0\bar{7}3$	1.978	< 0.6	1.3
$0\bar{4}2$	1.198	< 2.0	0.1				
$0\bar{5}1$	1.220	< 2.0	1.9				
$0\bar{1}3$	1.224	7.2	-6.9				
013	1.259	<2.0	-1.7				
$0\bar{2}3$	1.274	5.9	5.9				
051	1.277	6.1	6.7				
042	1.290	< 2.0	-0.9				
023	1.340	6.5	7.8				
$0\bar{3}3$	1.362	6.1	10.7				
$0\bar{5}2$	1.382	4.3	-4.3				
$0\bar{6}1$	1.444	<2.0	0.5				
033	1.455	<2.0	2.8				
$0\bar{5}2$	1.483	<2.0	2.9				
$0\bar{4}3$	1.485	<2.0	0.2				
061	1.503	<2.0	1.5				
$0\bar{6}2$	1.580	<2.0	2.3				
043	1.597	<1.8	2.1				
$0\bar{1}4$	1.602	<1.8	-1.6				
$0\bar{5}3$	1.632	<1.8	-0.2				
014	1.638	<1.8	2.2				
$0\bar{2}4$	1.658	2.2	-3.2				
$0\bar{7}1$	1.672	<1.8	-4.0				
062	1.686	1.8	1.0				
$0\bar{3}4$	1.702	2.5	2.7				

TABLE 11. Experimental Atomic Scattering Curve.

2 sin Θ	f
.1	5.70
.2	5.32
.3	4.85
.4	4.40
.5	3.92
.6	3.46
.7	2.92
.8	2.48
.9	2.02
1.0	1.63
1.1	1.32
1.2	1.10
1.3	.90
1.4	.72
1.5	.60
1.6	.49
1.7	.40
1.8	.33
1.9	.30

Appendix II.

Trial Structures (hol) Zone.

Trial Structures (hol) Zone.

z-coordinates of the atoms were found by the methods discussed in section B, 2(b). In every case, structure factors calculated using these coordinates showed poor agreement with observed structure factors. Similar methods were used in each case in attempting to find modifications of the sets of coordinates which would give improved agreement, and a few typical examples are discussed here. These methods of refinement were applied to each set of coordinates obtained by the methods discussed in section B, 2(b). Both centrosymmetric and non-centrosymmetric structures were considered.

A. Centrosymmetric Structures.

(1). Refinement was attempted by the method found successful in the (hko) zone (section A, 2(d)), i.e., the use of scale diagrams of the molecule and of the unit cell. The x-coordinate was known from the (hko) projection, so that any atom could move in the (hol) projection only along a line defined by its x-coordinate.

In the first instance, the molecule was moved as an entity and attempts were made to place the atoms so that they made large contributions to planes of high intensity, and small contributions to planes of low intensity.

By this method, several trial structures were noted which gave reasonable discrepancy for a small number of planes, but in each case, the agreement became poor when more structure factors were calculated.

In order to ensure that no possible structure of this type had been overlooked, structure factors for the planes (001), (002) and (003) were calculated at each thirtieth along the c-axis and these values were graphed against the position of the molecule. From this graph, the positions of the molecule at which there was agreement between observed and calculated structure factors for these planes could be found. The limit of refinement with this particular model was then reached, and any further refinement therefore necessitated the movement of individual atoms relative to the other atoms in the molecule.

The first atoms considered were the oxygen atoms of the carboxyl group. From an examination of the contributions of these two atoms to planes which gave poor agreement between observed and calculated structure factors, it was decided that agreement would be improved by an increase in the z-coordinate of one, with a decrease in the z-coordinate of the other. An interchange of the single- and double-bonded oxygens effected the required movements in z-coordinates. Using these new coordinates of the oxygen atoms, together with the coordinates from the best previous trial structures, structure factors were calculated for the (hol) zone and the discrepancy expressed as

$$\frac{\sum \left(|F_{obs}| - |F_{calc}| \right)}{\sum |F_{obs}|}$$

was calculated to be 38%. This is not very good, but a very low discrepancy in this zone was not expected due to the preponderance of planes of low intensity.

It was decided to extend the reasoning applied to the oxygen atoms to the rest of the molecule. From the planes giving poor agreement in the previous structure, deductions about the required directions of movement of the atoms were made.

For example, the observed and calculated structure factors of planes (202) and ($20\bar{2}$) were in poor agreement. Improvement could be effected by an increase in the z-coordinate of C_1 together with a decrease in the z-coordinates of C_3, C_5 and O_2. The effect of these movements of the atoms on planes showing good agreement was then considered, and attempts were made to find movements of the atoms which would not interfere with the planes giving satisfactory calculated structure factors while improving the unsatisfactory ones.

Consideration of the possible non-planarity of the molecule and of the latitude possible in molecular dimensions (section B, 2(b)) showed that a considerable range of atomic movements could be derived. Despite many attempts, no improvement was recorded; invariably, better agreement with observed structure factor for some planes resulted in poorer agreement for others, and the trial structure giving a discrepancy of 38% remained the most satisfactory of the centrosymmetrical structures.

B. Non-centrosymmetrical Structures.

Since all attempts to obtain a centrosymmetric structure had been unsuccessful, the possibility of a non-centrosymmetric structure was investigated.

In this case, the position of both molecules had to be considered, since there was no centre of symmetry. The angle of inclination of both molecules to the c-axis was the same in magnitude, since the (hko) projection was centro-symmetric, but there were two possible directions of inclination. These give four possible sets of coordinates for any trial structure under consideration.

For any postulated model of the molecule, the positions of the molecules in the unit cell were found, by calculation of the structures of the three intense planes (001), (101) and $(10\bar{1})$ at positions of a reference atom every $^1/18$th along the c-axis. The first molecule was placed at 0 and the second molecule moved through the range $^1/18$th to $^9/18$ths. The first molecule was then placed at $^1/18$th and the second moved through the range $^1/18$th to $^9/18$ths: this procedure was continued until all possible combinations for this particular model had been considered. Positions of the reference atom were noted at which good agreement between observed and calculated structure factors of the three planes was found and structure factors for other planes in the (hol) zone calculated.

It was noted that changes in geometric structure factor altered the calculated structure factor much less in non-centresymmetric structures than in centrosymmetric structures. A similar effect was investigated by Wilson[33], who postulated a structure with the same symmetry as a correct structure, but with an unrelated arrangement of atoms. Mathematical calculation of discrepancies showed that the discrepancy for an incorrect centrosymmetric structure was $\sqrt{2}$ times as great as that for an incorrect non-centrosymmetric structure. For a non-centrosymmetric structure to be established, therefore, the discrepancy must be less than that considered satisfactory for a centrosymmetric structure.

Attempts were made to find a non-centrosymmetric structure, considering various models of the molecule both planar and non planar, but without success. The number of possibilities to be investigated was very great, since there was very little indication of the position of the molecules in this projection. It was therefore decided that further attempts to evaluate the structure would be impracticable if the cell had no centre of symmetry.

C. Fourier Synthesis.

In the hope that more definite information would be obtained regarding the required movement of the atoms, it was decided to try to refine the trial structure giving a 38% discrepancy by two-dimensional Fourier methods.

Fourier syntheses were carried out projecting down the b-axis using the signs of the structure factors calculated from the trial structure which gave 38% discrepancy. The number of planes which could be included in this synthesis was limited, since the preponderance of planes of low structure factor meant that changes in sign could occur readily with small movements of the atoms. Two Fourier syntheses were calculated, since it could be seen from the structure factor equation

$$F_{hol} = 2f \sum \cos 2\pi \left(\frac{hx}{a} + \frac{lz}{c}\right)$$

that a change of 180° in coordinate of all the atoms altered the signs of structure factors where l was odd, but not where l was even.

Each Fourier synthesis was carried out as described in section B (3).

The electron density contour map showed resolution of only two atoms, the ring oxygen atom and one of the oxygen atoms of the carboxyl group. Two of the other atoms were represented only as marked irregularities in the countour lines round the ring oxygen; the remaining four formed two ellipses. This poor resolution allowed a considerable latitude in estimation of the centres of the peak, and no improvement in the structure was noted.

It was thought that the coordinates of the two resolved atoms would be fairly accurate and so from these as reference atoms, the coordinates of the other atoms were calculated by Method (a) (section B, 2(b)). Structure factors calculated from these coordinates for the observed planes in the (hol) zone showed a discrepancy of 35%. This discrepancy probably represented a rather better approximation to the structure than it appeared to do, because the high proportion of low structure factors made a low discrepancy difficult to obtain. A comparison of this discrepancy with that in the (hko) zone probably gives a better idea of the validity of the structure. A similar situation was found in para-nitroaniline.[34]

The discrepancy in both zones was expressed as the fraction

$$\frac{\sum\left(|F_{obs}| - |F_{calc}|\right)}{\sum |F_{max}|}$$

where F_{max} was the maximum possible structure factor for each plane. The discrepancy in the (hol) zone, D, was then calculated from

$$D = D' \times \frac{F}{F'}$$

where D' = discrepancy in the (hko) zone

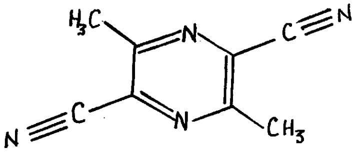
F, F' = fractions for (hol) and (hko) zones respectively.

D was calculated to be 30%.

It was decided therefore to calculate an (hol) Fourier synthesis applying the signs of the structure factors calculated from this set of coordinates to the observed structure factors. The method was exactly as described in section B (3). The electron density map drawn from these Fouriers were very similar in appearance to the preceding Fourier syntheses and no further information, or refinement, was recorded.

Part II.

The Crystal and Molecular Structure
of
2:5 Dicyano 3:6 Dimethyl Pyrazine.



Introduction.

The investigations of the structure of six-membered nitrogen heterocyclic compounds by X-ray methods have been concerned mainly with pyrimidine derivatives such as amino-chloropyrimidines[35], and 4:6 dimethyl 2 hydroxy pyrimidine[36]. No structural investigations of pyrazine or of its derivatives by X-ray methods have so far been reported.

Pyrazine, itself, has been examined by electron diffraction methods by Pauling and Schomaker[10] who concluded that the structure of pyrazine was identical with that of benzene. Their calculations showed that, if the carbon to carbon bond length was assumed to be 1.39Å as in benzene, the carbon to nitrogen bond length was 1.35Å, with the atoms of the ring forming a planar hexagon. Planarity was also indicated by studies of the observed and calculated dipole moments[37].

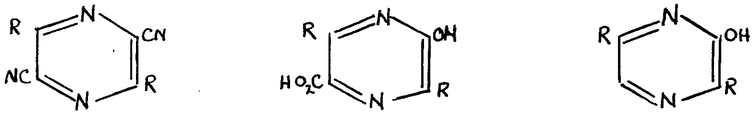
The object of the present investigation was the elucidation by X-ray methods of the crystal and molecular structure of 2:5 dicyano 3:6 dimethyl pyrazine. This was expected to give a value for the length of the carbon to nitrogen triple bond linked to an aromatic system, a value which has not before been reported.

Such an investigation, also, it was hoped, would yield information about the effect of the various substituents on the dimensions of the ring and about their mutual interaction.

Any conjugation between the cyano group and the pyrazine ring should be reflected in a decrease in length of the carbon to carbon bond linking them.

The methyl group is linked by a formal single bond to a conjugated system, viz. the pyrazine ring system and therefore hyperconjugation[41] between the substituent and the ring may take place. This involves the assumption that the carbon to hydrogen bonds can be treated as one quasi-triple bond. The effect of this hyperconjugation is most noticeable in the acceptor bond, i.e., the formal single bond linking the methyl group to the conjugated system. This bond has been reported to be considerably shorter than a corresponding single bond in several compounds[38]. The hyperconjugation of the methyl group may also influence the cyano group and affect the bond lengths.

It was hoped, too, that the elucidation of the structure of 2:5 dicyano 3:6 dimethyl pyrazine might provide an explanation for the remarkable hydrolytic reaction of the 2:5 dicyano 3:6 disubstituted pyrazines. This was first recorded by Gastaldi[39] who formulated the reaction



I II

This reaction takes place under relatively mild conditions.

For example, Sharp and Spring[40] report that 2:5 dicyano 3:6 dimethyl pyrazine (I) gave a 50% yield of the acid (II) when warmed with 15% potassium hydroxide.

Experimental.

(1). Preparation.

The sample of 2:5 dicyano 3:6 dimethyl pyrazine was obtained from Professor F.S. Spring[40]. Recrystallisation from benzene gave single crystals, m.p. 210°C. These were tabular in shape, and showed well-developed faces in two dimensions.

(2). Optical Measurements.

a). Extinction was noted under the polarising microscope at positions 90° apart.

b). Refractive indices in the directions in the plane of the plate were determined by the Becke line method[45]. In the direction perpendicular to the plane of the plate, the refractive index was measured using a modified Pulfrich refractometer by Dr. Holgate of the Geology Department of this University[45]. The values found were:

$\alpha = 1.58$
$\beta = 1.615$ $\qquad\qquad \beta \approx \gamma = 1.617 \pm 0.03$
$\gamma = 1.620$

α, β and γ were measured in directions parallel to the a, b, and c axes respectively.

(3). Density.

The density, measured by flotation in potassium iodide solution, was 1.296 gm./ml.

(4). X-Ray Investigation.

All photographs were taken using copper targets giving

CuKα radiation ($\lambda = 1.54$Å). The Cu Kβ radiation was eliminated by a nickel filter. Rotation and oscillation photographs were taken using a cylindrical camera of radius 3.00 cms.

Zero layer moving film photographs and multiple film series about each of the three unit cell axes were taken on a horizontal Weissenberg apparatus with cameras of radius 3.99 cms. and 3.94 cms.

(5). Unit Cell Dimensions.

a = 6.14Å ±.02Å. b = 8.71Å ±.03Å. c = 15.43Å ±.03Å

Volume = 825.2 cuÅ.

No. of molecules in unit cell = 4.

Density observed = 1.296 gm./ml.

Density calculated = 1.276 gm./ml.

(6). Crystal System.

Oscillation photographs about each of the three unit cell axes showed symmetry. The three axes were therefore mutually perpendicular and the crystal system was orthorhombic.

(7). Space Group.

Observed reflections were:

(hol) only when l = 2n.

(hko) only when h = 2n

(okl) only when k = 2n.

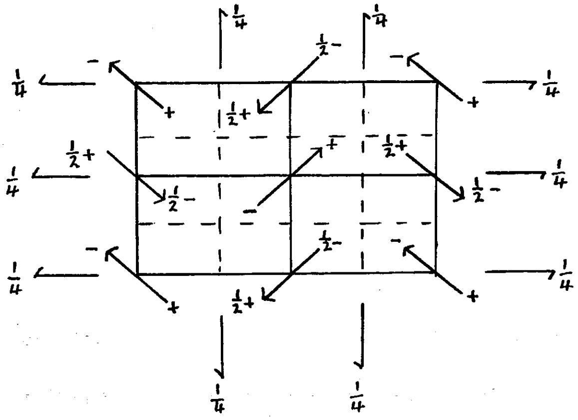
The space group was therefore P_{bca}.

The symmetry of this space group required eight asymmetric units. Since there were only four molecules of 2:5 dicyano 3:6 dimethyl pyrazine in the unit cell, the molecules must be centrosymmetric, with the centre of symmetry lying at point positions

a) 000, $\frac{1}{2}\frac{1}{2}0$, $0\frac{1}{2}\frac{1}{2}$, $\frac{1}{2}0\frac{1}{2}$

b) $00\frac{1}{2}$, $\frac{1}{2}\frac{1}{2}\frac{1}{2}$, $0\frac{1}{2}0$, $\frac{1}{2}00$.

The following diagram shows the symmetry elements of a projection down any of the three unit cell axes.



Structure Determination.

The investigation of the crystal and molecular structure of 2:5 dicyano 3:6 dimethyl pyrazine was carried out by trial structure methods, followed by refinement by two-dimensional Fourier syntheses (Part I, p.10). Before a trial structure could be suggested, it was necessary to postulate dimensions of the molecule.

a). Dimensions of the Molecule.

(i) Ring Bonds.

As stated in the Introduction, electron diffraction results[10] showed that pyrazine had a planar structure with carbon to carbon bond lengths of 1.39Å, and carbon to nitrogen bond lengths of 1.35Å. These were taken as the bond lengths in the ring for the preliminary work.

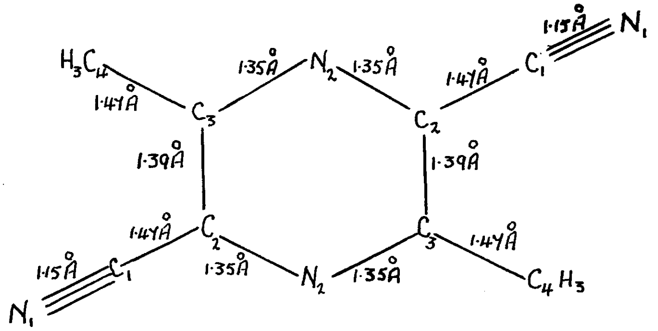
(ii) Methyl Group.

Taking into consideration the possible effect of hyperconjugation[41], it was decided to assume a bond length of 1.47Å for the bond linking the methyl group to the ring as in durene[42] and the methyl acetylenes[38].

(iii) Cyano Group.

The carbon to nitrogen triple bond length has been measured in methyl cyanide[38] to be 1.15Å. Since there would be conjugation of the cyano group with the bonds of the ring, the bond linking the cyano group to the ring was taken as 1.47Å.

(iv). The following diagram shows the bond lengths assumed in the molecule of 2:5 dicyano 3:6 dimethyl pyrazine



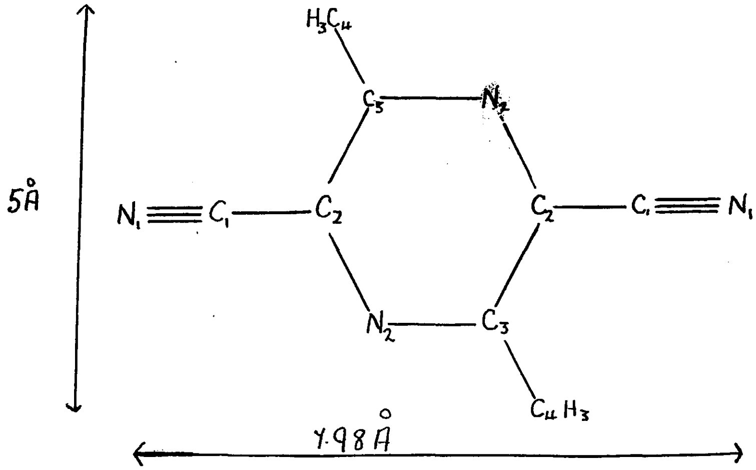
b). Factors indicating position of the molecule in the unit cell.

(i) Refractive Indices.

Since the values of the three refractive indices in directions parallel to the unit cell axes were approximately equal, the molecules were probably inclined to each of the three axes.

(ii) Dimensions.

The length of the molecule was 7.98Å, the breadth was 5Å, and the thickness was assumed to be 3.7Å[43].



The dimensions of the unit cell containing four molecules were: a = 6.14Å, b = 8.71Å, c = 15.43Å.

From a consideration of these dimensions, it was possible to place the molecules with their planes approximately perpendicular to either the *b* or the *c* axis. In order to establish which of these approximate orientations was correct, a brief investigation of both (hko) and (hol) zones was carried out. Once the more reasonable orientation had been established, a full investigation of the corresponding zone (hko) or (hol) would be made, and the remaining two zones then investigated using as a basis the structure derived from the refinement of the first zone.

A. Investigation of the (hko) Zone.

(1). Observed Structure Factors.

The estimation of the intensities of reflections from planes in the (hko) zone was carried out by the multiple film technique[17]: the intensities were compared visually. To obtain a wide range of intensities, two multiple film series were taken, the second having an exposure comparable with that of the weakest film of the first series. The range of intensities was 2,000 to 1, and 88% of the possible reflections were recorded.

These intensities were corrected for Lorentz and polarisation factors (Part I, section A1), but absorption corrections were not necessary, since the crystals were of fairly uniform cross-section. The observed structure factor, F_{obs}, was calculated from

$$F_{obs} = \pm \sqrt{I_{corr.}}$$

A list of comparative structure factors for all planes was prepared. These structure factors were not placed on an absolute scale, but were scaled by comparison with the structure factors calculated for trial structures.

(2). Trial Structures.

(a) Assuming a planar molecule with thickness 3.7Å[43], the tilt of the molecule to the c-axis was calculated to be $\cos^{-1}\frac{4 \times 3.7}{15.43} = 16.4^\circ$. This may be made up of inclinations along different bonds as axes or of an inclination about one bond.

(b) A study of the observed structure factors showed that the planes (200), (270), (280), (210) were all strong. These comparative values, together with the variations in intensities of the (hoo) and (oko) planes were used in attempts to fix the positions of the atoms in the unit cell.

(c) The method of procedure was as follows: A scale drawing of the (hko) projection plane was made. A model of the postulated molecule was made in metal with small holes at the positions of the atoms. A parallel beam of light was allowed to fall on the model of the molecule, and an image of the molecule projected on to the drawing of the (hko) projection. The model could be tilted at any angle and in any direction, and its projection noted on the diagram of the (hko) projection. On this diagram were drawn the traces of the strong planes and of the axial planes, and the molecule moved so as to satisfy the structure factor values of these planes. When a structure was found which gave good agreement between observed and calculated structure factors for these planes, the theoretical structure factors for the remainder of the planes in the (hko) zone were calculated. In this way, several structures were investigated, and a structure obtained which gave 38% discrepancy, expressed as

$$\frac{\sum\left(|F_{obs}| - |F_{calc}|\right)}{\sum |F_{obs}|}$$

(3). Calculation of Theoretical Structure Factors.

a). The calculated structure factor for a plane (hkl) when the space group is P_{bca} is given by

$$F_{(hk\ell)} = 8\sum f \cos 2\pi\left(hx - \frac{h-k}{4}\right) \cos 2\pi\left(ky - \frac{k-\ell}{4}\right) \cos 2\pi\left(\ell z - \frac{\ell-h}{4}\right)$$

For planes in the (hko) projection, this reduces to

$$F_{(hko)} = 8\sum f \cos 2\pi hx \cos 2\pi ky \qquad \text{when } \begin{matrix} h+k = 2n \\ k+\ell = 2n \end{matrix}$$

$$F_{(hko)} = -8\sum f \sin 2\pi hx \sin 2\pi ky \qquad \text{when } \begin{matrix} h+k = 2n+1 \\ k+\ell = 2n+1 \end{matrix}$$

where $\underline{x},\underline{y}$ are the atomic coordinates

$\underline{f}$ is the atomic scattering factor.

b). The atomic scattering factor was found from the atomic scattering curve used in the investigation of the crystal structure of durene[42]. This scattering curve was used throughout the preliminary investigation.

(4). Refinement by Fourier Syntheses.

The signs of the structure factors calculated for the structure giving 38% discrepancy were allocated to the corresponding observed structure factors and a Fourier synthesis carried out projecting down the a-axis on to the (100) plane.

For the purpose of the computation, the a and b axes were divided into sixtieths with $a/_{60}$ = .1023Å and $b/_{60}$ = .1452Å. The summation was carried out over one eighth of the unit cell ($a/_4$ by $b/_2$) by means of Robertson's strips which gave three-figure accuracy[26].

The electron density contour map drawn from this Fourier summation showed poor resolution, and its interpretation was found to be impossible.

It seemed, therefore, that the molecule did not lie with its plane approximately perpendicular to the c-axis, and so the alternative orientation was considered by investigation of the (hol) zone.

B. Investigation of the (hol) Zone.

(1) Observed Structure Factors.

The intensities of the planes in the (hol) zone were estimated as in the (hko) zone (section A 1). The range of intensities was 2,000 to 1 and 66% of the possible reflections were recorded.

From intensities corrected for Lorentz and polarisation factors, the observed structure factors were calculated from

$$F_{obs} = \pm\sqrt{I_{corr.}}$$

A list of comparative observed structure factors for all planes in the (hol) zone was prepared. These were not placed on an absolute scale, but scaled later by comparison with calculated structure factors.

(2) Trial Structures.

a). The tilt of the molecule to the b-axis was $\cos^{-1} \frac{2 \times 3.7}{8.71} = 31.8^{\circ}$ assuming a planar molecule of thickness 3.7Å [43].

b). The planes (200), (206), (406), (2,0,16), were strong; there was a considerable variation in intensities in the series of planes (hoo) and (ool). These values were used in placing the molecule in the projection.

c). The procedure adopted was the same as in section A 2c. Two sets of coordinates were noted which gave reasonable agreement for the strong planes and the axial planes and the theoretical structure factors were calculated for each of these structures. One gave a 31% discrepancy (trial structure 21), the other a 35% discrepancy (trial structure 40). The main difference in the two structures was the interchanging of the cyano and methyl groups with resultant small differences in the positions of the other atoms.

Since a structure giving a reasonable discrepancy had been obtained, it was assumed that the molecule lay with its plane approximately perpendicular to the b-axis, and so a full investigation of the (hol) zone was made.

(3). Calculation of Theoretical Structure Factors.

In space group P_{bca}, the structure factor for a plane (hol) reduces to

$$F_{(ho\ell)} = 8\sum f \cos 2\pi hx \cos 2\pi \ell z \qquad \text{when } \begin{matrix} h+k = 2n \\ k+\ell = 2n \end{matrix}$$

$$F_{(ho\ell)} = -8\sum f \sin 2\pi hx \sin 2\pi \ell z \qquad \text{when } \begin{matrix} h+k = 2n+1 \\ k+\ell = 2n+1 \end{matrix}$$

(4) Fourier Refinement.

a) Trial structure 40.

The signs of the structure factors calculated for planes in the (hol) zone were allocated to the corresponding observed structure factors and a Fourier synthesis carried out projecting down the b-axis on to the (010) plane (Fourier 1). For the computation, both a and c axes were divided into sixtieths, $a/60 = .1023\text{Å}$ and $c/60 = .2572\text{Å}$, and the summation carried out over one-eighth of the unit cell ($\frac{a}{2}$ by $\frac{c}{4}$) by means of Robertson's strips[26].

The electron density contour map drawn from this synthesis showed resolution of only the two carbon atoms of the ring; the other atoms lay so near to the glide plane that their reflections across this plane coalesced. High peaks were observed at the positions of the side chains, but there was little indication, either from the height or the shape of the peaks as to which represented the cyano and which represented the methyl groups. Attempts to find coordinates which gave better agreement between observed and calculated structure factors were unsuccessful.

Since the main difficulty in interpreting the Fourier map arose from the poor resolution obtained (only two of the six atoms in the asymmetric unit were resolved), it was decided to attempt refinement by an "error" synthesis. This method had been employed successfully in the elucidation of the structure of penicillin[44] where the resolution obtained in a normal Fourier synthesis was also poor.

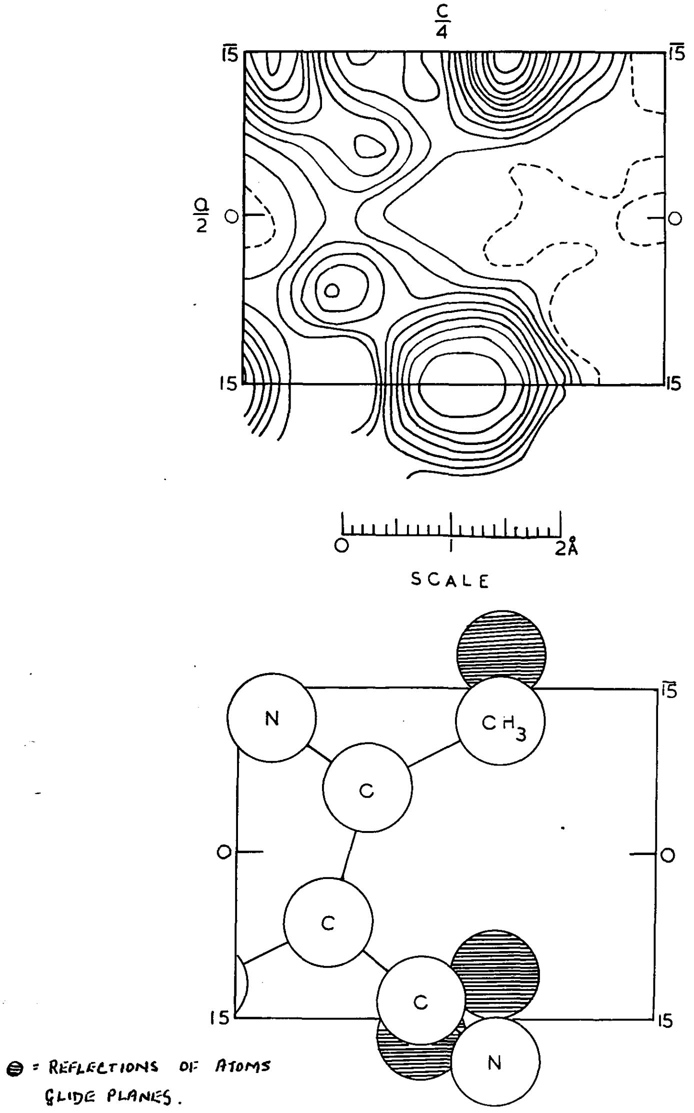
In the "error" synthesis the coefficients of the normal Fourier synthesis were replaced by the expression ($F_{obs.}$ - $F_{calc.}$), i.e., the discrepancy. As in a normal Fourier synthesis, only those planes were included where the sign of the coefficient was reasonably well established. The computation for this Fourier synthesis (Fourier 2) was carried out exactly as in Fourier 1 and the electron density mapped with contour lines drawn every $\frac{1}{2}$ electron per Å. This gave some indication of the required direction of movement of the atoms, but it was difficult to assess the magnitude of the movements, and no refinement of the structure was obtained.

b) Trial structure 21.

The signs of the structure factors calculated from the coordinates of trial structure 21 were allocated to the corresponding observed structure factors and a Fourier synthesis (Fourier 3) carried out as in Fourier 1.

The electron density contour map (fig.4) showed resolution of the two carbon atoms of the pyrazine ring. The remaining atoms were not resolved, and the side chains could not be identified either from the height or the shape of the peaks.

No improvement in discrepancy was noted from various sets of coordinates chosen from this electron density map, and again refinement by "error" synthesis was attempted.



⊖ = REFLECTIONS OF ATOMS GLIDE PLANES.

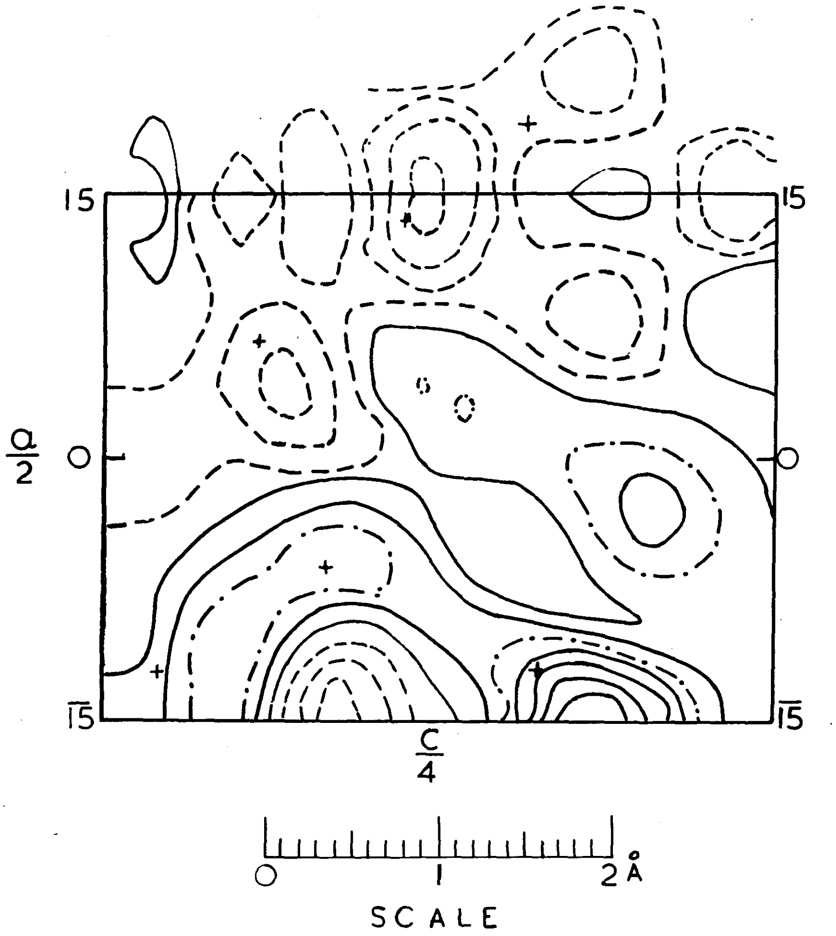
Fig.4. 2:5 Dicyano 3:6 Dimethyl Pyrazine, Fourier 3.
Projection along b-azis. Each contour line represents an electron density increment of one electron per $Å^2$.
The line representing an electron density of one electron per $Å^2$ is dotted.

The error synthesis (Fourier 4) was carried out as in the case of Fourier 2. The electron density map (fig.5) showed some indications of the direction of the required movements, but magnitude of the movements was difficult to estimate.

The high peak at $x = \frac{15}{60}$ a, $z = \frac{11}{60}$c, suggested that the carbon of the methyl group should be moved quite considerably in this direction. However, this meant that the bond between the methyl group and the carbon atom of the ring would have had to be greater than 1.54Å. The possibility that this peak was due to the contribution of the hydrogen atoms of the methyl group was therefore considered. For a preliminary investigation, the "centre of gravity" of the hydrogen atoms was assumed to be at the centre of the peak in the difference Fourier. The contribution of the hydrogen atoms for any plane was divided by one-sixth compared with the contribution of the carbon atoms and included in the geometric structure factor for that plane.

Structure factors calculated from the coordinates of trial structure 21 including the hydrogen atoms (trial structure 40) showed a discrepancy of 25.1%, i.e., a decrease of 5.5% resulting from a consideration of the contribution of the hydrogen atoms.

It seemed, therefore, that the hydrogen atoms made a considerable contribution to the structure factors. This fact may explain the noticeable spreading of the electron



<u>Fig.5.</u> <u>2:5 Dicyano 3:6 Dimethyl Pyrazine.</u>

Difference Fourier - Fourier 4. Projection along b-axis. Each contour line represents an electron density increment of one electron per $Å^2$.

——— represents positive electron density contours.

----- represents negative electron density contours.

-.-.- represents one electron contour line.

density round the methyl group (fig.4). There are two slight irregularities in the two-electron line which suggest that hydrogen atoms may lie there.

Further investigation of this effect is required, by finding the actual positions of the hydrogen atoms, and by use of a separate scattering curve for the hydrogen atoms. This is necessary, since the scattering power of hydrogen decreases much more rapidly with increasing 2 sin θ value than does the scattering power of carbon or of nitrogen. It is hoped that further refinement by "error" syntheses and by Fourier syntheses may then be successful.

A list of calculated and observed structure factors for trial structures 21 and 40 is given in Appendix III, Table 12.

(5). Conclusions.

The investigation of the (hol) zone gave a structure which showed a 30.6% discrepancy. This discrepancy decreased to 25.1% when the contribution of the hydrogen atoms was taken into consideration. Some indication of the position of these hydrogen atoms may be found from Fourier 3 (fig.4), and a more detailed investigation of the effect of the hydrogen atoms will be made. This may then allow refinement by Fourier and "error" syntheses.

Appendix III.

Tables of Observed and Calculated Structure Factors.

Table 12. Observed and Calculated Structure Factors (hol) zone.

(hol)	2 sin θ	T.S. 21		T.S. 40	
		$F_{obs.}$	$F_{calc.}$	$F_{obs.}$	$F_{calc.}$
002	.200	66.2	82.1	70.5	66.7
102	.321	7.2	29.4	7.7	16.8
004	.399	55.5	-58.2	59.1	-59.5
104	.471	9.5	-5.9	10.1	9.7
200	.501	80.7	-83.7	86.2	-101.2
202	.540	9.7	-2.6	10.3	7.1
006	.599	30.0	24.2	32.0	35.4
204	.641	31.3	36.7	33.4	37.9
106	.649	42.3	-31.5	48.2	-38.8
206	.781	50.5	-44.0	53.8	-59.5
008	.798	8.9	-3.7	9.5	-13.4
108	.837	18.1	-14.9	19.3	-16.9
304	.851	10.0	-2.2	10.6	-11.3
208	.942	23.5	-28.1	25.1	-24.1
306	.961	18.6	27.1	19.9	31.6
00,10	.998	27.0	-24.0	28.9	-20.6
402	1.023	18.1	-10.0	16.9	-14.7
404	1.079	6.8	-5.5	7.3	-6.2
308	1.096	16.7	26.4	17.8	36.5
2,0,10	1.117	7.1	2.4	7.5	-0.6
406	1.168	28.2	14.5	32.1	18.9
00,12	1.197	9.3	15.3	9.9	7.0
3,0,10	1.249	12.0	5.1	12.9	0.9
408	1.282	10.5	20.8	11.3	16.2
2,0,12	1.297	9.9	-5.9	10.5	-7.4
504	1.316	7.6	3.2	8.1	7.6
506	1.389	12.5	-4.4	13.3	-6.7
00,14	1.397	4.7	6.2	5.0	2.7
3,0,12	1.414	4.7	-4.2	5.0	-0.6
4,0,10	1.414	10.2	8.9	10.9	11.8
1,0,14	1.419	10.8	-17.5	11.5	-16.0
508	1.487	6.2	-10.7	6.6	-11.5
600	1.504	4.6	-3.0	4.9	-6.2
00,16	1.596	10.2	-9.6	10.9	-6.8
1,0,16	1.616	12.5	-17.2	13.4	-15.9
2,0,16	1.672	11.9	11.2	12.7	8.4
608	1.703	6.5	5.7	7.1	8.5
5,0,12	1.733	6.0	6.5	6.4	4.0
3,0,16	1.765	5.7	-0.7	6.0	-1.8
6,0,10	1.794	10.3	-4.7	10.9	-5.9
1,0,18	1.813	7.5	-5.9	8.1	-8.2
706	1.854	4.3	-4.9	4.5	-3.5
4,0,16	1.885	5.0	-3.7	5.3	-1.8
708	1.928	5.1	-3.3	4.3	-2.8

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