

The Structure of Heterocyclic Compounds Containing Nitrogen. I. Crystal and Molecular Structure of *s*-Tetrazine

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(Received 9 January 1956)

The detailed structure of *s*-tetrazine has been established by means of two-dimensional Fourier analysis. The molecule is a planar distorted hexagon with the following bond lengths and angles:

$$\text{C-N} = 1.334 \text{ \AA}, \text{ N-N} = 1.321 \text{ \AA}; \text{ C-N-N} = 115^\circ 57', \text{ N-C-N} = 127^\circ 22'.$$

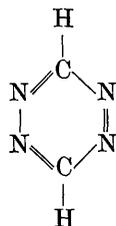
The molecular structure is discussed with reference to the electronic structure, and the measured C-N bond length is compared with that calculated by the method of molecular orbitals.

Introduction

A considerable amount of theoretical work has been carried out in order to correlate the physical and chemical properties of heterocyclic compounds with their electronic structures. However, the lack of sufficiently accurate experimental data on the molecular structures of these compounds necessitated the adoption of a number of assumptions which limit the reliability of the results of the theoretical calculations.

Careful X-ray investigations of the molecular structure of a few heterocyclic compounds have therefore been undertaken recently by various authors. Work on conjugated heterocyclic molecules containing nitrogen is also in progress in our laboratory.

This paper reports the results of an investigation of the detailed structure of *s*-tetrazine:



Experimental

As reported in a previous communication (Bertinotti, Giacomello & Liquori, 1955) the unit cell of *s*-tetrazine is monoclinic, space group $C_{2h}^5-P2_1/c$, and contains two centrosymmetric molecules. Dimensions are:

$$a = 5.23 \pm 0.01, \quad b = 5.79 \pm 0.01, \quad c = 6.63 \pm 0.01 \text{ \AA}; \\ \beta = 115^\circ 30' \pm 15'.$$

Diffraction intensities were collected at about -20°C . from a crystal grown by slow sublimation and enclosed in a sealed glass capillary. ($0kl$) reflexions were recorded on multiple Weissenberg photographs up to $s = 1.170$, using filtered Cu radiation. ($h0l$)

reflexions were recorded on a set of precession photographs taken with different exposure times. Filtered Mo radiation was used in connection with a 30° precession angle so that reflexions up to $s = 1.340$ could be observed.

Intensities were visually estimated with the aid of standard scales by two independent observers. After application of the appropriate Lorentz and polarization corrections, the statistical method of Wilson (1942) and the non statistical method of Kartha (1953) were employed in order to place the F^2 on the absolute scale.

These two methods yielded very different results. It was eventually decided to use for comparison the absolute intensities of a few reflexions given by a crystal of benzoic acid of approximately the same size and shape. However, a scale factor which disagreed with those calculated with both Wilson's and Kartha's methods was obtained. This last scale factor was adopted during the preliminary stage of the structure determination and has been found to be very close to the final value.

Non-randomness in the atomic distribution and overlapping of electron clouds in the projected structure of *s*-tetrazine seems the most likely explanation for the failure of Wilson's and Kartha's methods respectively.

By comparing the structure amplitudes derived from the experimental intensities with those calculated from the atomic coordinates it was realized that the three strongest reflexions, namely 100, $10\bar{2}$, and 011, were strongly extinguished. The intensities of these reflexions were therefore re-measured, using a very small crystal. Significantly larger values were observed for the intensities of the 100 and $10\bar{2}$ reflexions while an increase of only a few percent of its former value was observed for the intensity of the 011 reflexion, which was the most intense. In the course of the refinement of the coordinates these new corrected values were employed for the 100 and $10\bar{2}$ reflexions

while the calculated value was used for the 011 reflexion.

Structure determination

(a) Electron-density projections along [100] and [010]

As described in the previous communication, application of the Fourier-transform method to the projection along [010] and of Harker-Kasper inequalities to the projection along [100] gave most of the signs for the Fourier calculation of projections on both planes. A first set of atomic coordinates was derived and then refined in the usual way (Bertinotti, Giacomello & Liquori, 1954).

In the calculation of the structure factors McWeeny's (1951) atomic scattering factors were employed, and through most of the refinement process a common isotropic thermal factor was applied. In the final stage anisotropic thermal corrections were used and the contributions of the hydrogen atoms were taken into

account. Finally ($F_o - F_c$) syntheses were computed for a final adjustment of the atomic coordinates and also for locating the hydrogen atoms.

The final Fourier maps are shown in Fig. 1. The very satisfactory separation of the atomic clouds at projected distances of about 0.8–0.9 Å is to be attributed to the relatively small entity of the thermal vibrations. The atomic peaks were in fact found to be rather sharp, as indicated by the values of the electron densities at the atomic centres and by the average curvatures on the [010] projection reported in Table 1.

Table 1. *Electron density and curvatures of Fourier peaks in the [010] projection*

Atom	ρ_0 (e.Å ⁻²)	$2\rho_0$ (e.Å ⁻⁴)
C	9.57	95
N ₁	11.44	107
N ₂	11.23	107

The final atomic coordinates are listed in Table 2.

Table 2. *Final atomic parameters*

Atom	x/a	y/b	z/c
C	0.2546	0.0153	0.1380
N ₁	0.1834	-0.1669	-0.0015
N ₂	0.0849	0.1795	0.1486

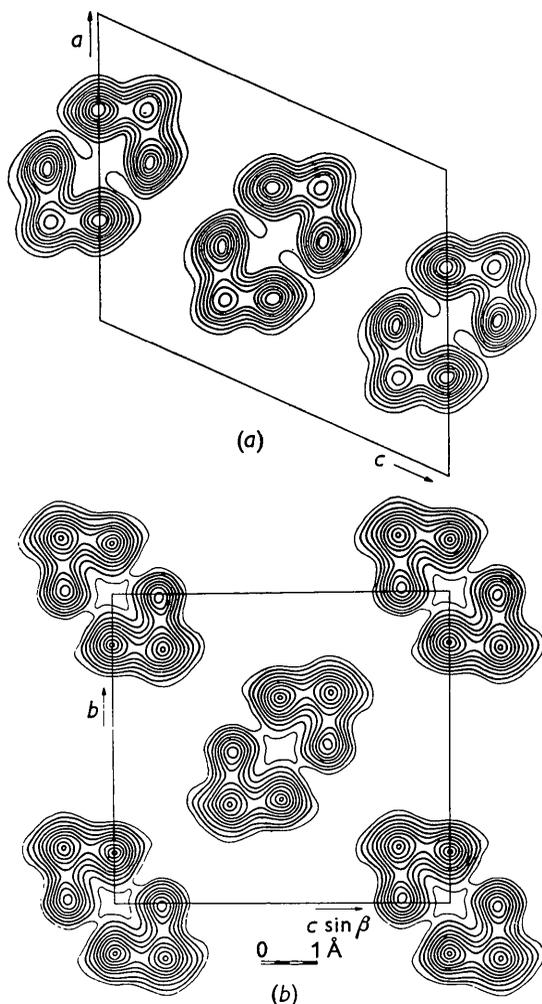


Fig. 1. Electron density projected (a) along [010], (b) along [100]. Contours are drawn at intervals of 1 e.Å⁻², starting from 2 e.Å⁻².

(b) Thermal vibrations

By inspection of the Fourier maps (Fig. 1) it can be noticed that the electron clouds associated with the nitrogen atoms projected along [010] and the electron clouds associated with atoms C and N₂ projected along [100] have a markedly elliptical shape. This effect was taken as an indication that the thermal vibrations, although relatively small are anisotropic.

A thermal correction of the form

$$\exp - [B_j^{\parallel} \cos^2(\omega_j - \psi_j) + B_j^{\perp} \sin^2(\omega_j - \psi_j)]$$

was separately applied to the contribution of the nitrogen atoms to the $h0l$ structure amplitudes. In this expression $B_j^{\parallel} = 8\pi^2(\bar{u}_j^{\parallel})^2$ and $B_j^{\perp} = 8\pi^2(\bar{u}_j^{\perp})^2$; $(\bar{u}_j^{\parallel})^2$ and $(\bar{u}_j^{\perp})^2$ are the mean square displacements of the j th atom parallel and perpendicular to the direction of maximum vibration respectively; ω_j and ψ_j are the angles which the normal to the reflecting plane and the direction of maximum thermal vibration make with the a^* axis.

Values of B_j^{\parallel} , B_j^{\perp} , and ψ_j are listed in Table 3 for the two nitrogen atoms.

Table 3

Atom	B^{\parallel} (Å ²)	B^{\perp} (Å ²)	ψ
N ₁	2.95	1.20	64° 30'
N ₂	2.95	1.20	25° 30'

An isotropic thermal correction was applied to the carbon atom with $B = 2.00$ Å².

Symmetry effects were found to make anisotropic thermal corrections for the projection along [100]

practically unimportant, and therefore a common isotropic thermal correction was applied to the contributions of all the atoms to the $0kl$ structure amplitudes.

It should be mentioned that the type of deformations of the electron-density distribution in both projections might possibly be accounted for by assuming rigid-body oscillations of the whole molecule about an axis perpendicular to its own plane, such as is found in crystalline benzene (Cox, Cruickshank & Smith, 1955). Since the molecule is very nearly hexagonal, the atomic electron densities should in fact be smeared by such an effect over six arcs of a circle, which in turn should become in projection arcs of ellipse because of the orientation of the molecular plane in the crystal (see Fig. 2).

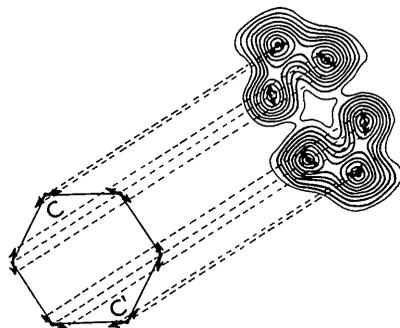


Fig. 2. Possible interpretation of the deformation of the projected electron-density distribution in terms of molecular oscillations.

(c) The hydrogen atoms

It is an interesting feature of *s*-tetrazine that only two hydrogen atoms are attached to the ring. By assuming that these two atoms are in the plane of the ring at 1 Å from the carbon atoms, their contribution to the structure amplitude was calculated. Having observed a decrease in the reliability factor R , ($F_o - F_c$) maps were prepared for both projections. The F_c 's corresponding to the projection along [010] were corrected by anisotropic thermal factors, while for the reasons discussed in § (b) those corresponding to the projection along [100] were corrected by an isotropic thermal factor.

The results are shown in Fig. 3, where ($F_o - F_c$) maps for the projections along [010] and [100] are reproduced. It will be noticed that the correspondence between the assumed positions of the hydrogen atoms, denoted by black circles, and the maxima of the ($F_o - F_c$) functions is very satisfactory in both maps.

The peak electron density for the hydrogen atom is about 0.6 e.Å⁻² in the [010] map and appears about doubled in the [100] map, where two hydrogen atoms, belonging to different molecules, overlap.

(d) Bond distances and bond angles

Bond distances and bond angles, calculated from the atomic coordinates of Table 2, are given in Table 4.

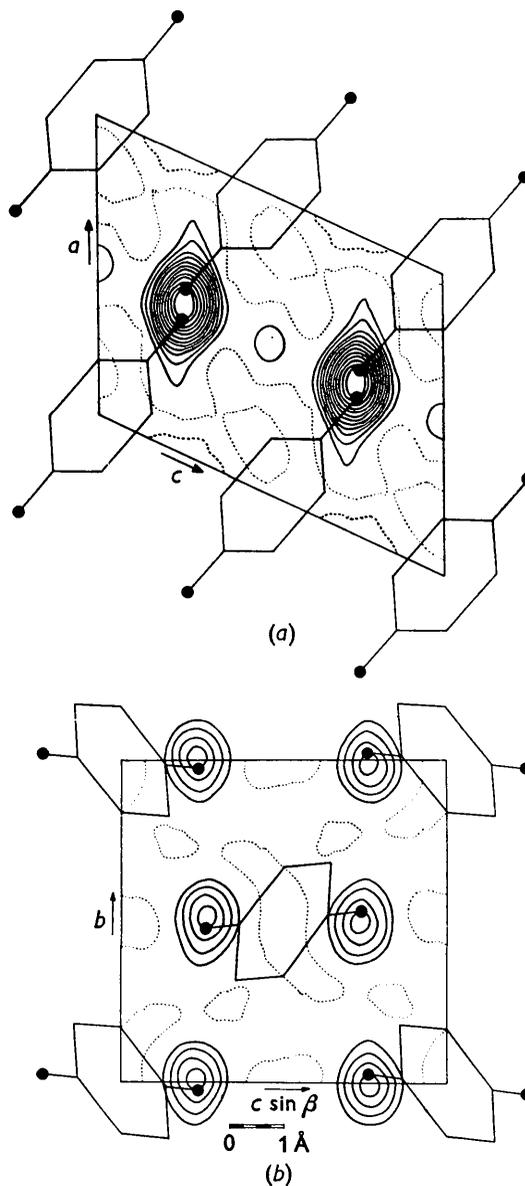


Fig. 3. ($F_o - F_c$) Fourier projection (a) along [010], (b) along [100]. The probable positions of hydrogen atoms are indicated by black circles. Contour lines are drawn at intervals of 0.1 e.Å⁻², starting from +0.3 e.Å⁻².

In (a) the broken line corresponds to -0.3 e.Å⁻² and the dotted line to zero; in (b) the dotted line is zero.

Table 4. Bond distances and angles

C-N ₁	1.345 Å	N ₂ '-N ₁ -C	116° 18'
C-N ₂	1.323	N ₁ '-N ₂ '-C	115° 37'
N ₁ '-N ₂	1.321	N ₁ -C-N ₂	127° 22'

Values averaged according to the D_{2h} symmetry of the molecule are:

$$\begin{aligned} \text{C-N} &= 1.334 \text{ \AA}, \quad \text{N-N} = 1.321 \text{ \AA}; \\ \text{C-N-N} &= 115^\circ 57', \quad \text{N-C-N} = 127^\circ 22'. \end{aligned}$$

The planarity of the molecule can be assessed within the experimental errors, and may be judged from the deviations of every atom from the plane

$$1.0003x + 1.1268y - 1.9522z = 1.$$

These are:

C	+0.008 Å	C'	-0.006 Å
N ₁	-0.004	N ₁ '	+0.006
N ₂	-0.007	N ₂ '	+0.009

(e) Accuracy

After corrections for thermal vibrations and inclusion of the contribution of the hydrogen atoms in the calculation of the structure factors, the following reliability factors were obtained:

$$R_{010} = 7.7\%, \quad R_{100} = 6.1\% \text{ (011 omitted).}$$

Values of F_o and F_c are listed in Table 5.

Table 5. Observed and calculated structure factors

hkl	F_o	F_c	F_c^+
100	26.90	31.24	28.36
200	-14.96	-16.12	-15.00
300	-11.42	-9.32	-9.68
400	0	1.40	—
002	8.32	10.80	8.68
004	-5.26	-7.12	-6.48
006	10.02	9.88	—
008	5.52	4.84	—
102	-14.20	-16.12	-14.84
104	2.04	1.28	0.92
106	7.34	8.76	—
202	-13.46	-14.00	-14.48
204	0	1.64	—
206	0	-0.88	—
302	-6.44	-6.84	—
304	-2.32	-2.00	—
402	-4.58	-4.00	—
404	0	-0.32	—
10 $\bar{2}$	32.34	29.12	31.32
10 $\bar{4}$	-11.42	-9.48	-10.28
10 $\bar{6}$	0	-0.40	—
10 $\bar{8}$	4.56	5.24	—
20 $\bar{2}$	0	0.84	0.48
20 $\bar{4}$	-8.00	-8.52	-7.88
20 $\bar{6}$	-6.88	-6.40	—
20 $\bar{8}$	0	0	—
30 $\bar{2}$	-9.62	-10.32	-9.80
30 $\bar{4}$	-11.48	-10.88	-11.24
30 $\bar{6}$	-4.94	4.32	—
30 $\bar{8}$	0	-0.44	—
40 $\bar{2}$	5.98	5.28	—
40 $\bar{4}$	-5.90	-5.80	—
40 $\bar{6}$	-2.80	-2.80	—
40 $\bar{8}$	4.98	4.16	—
50 $\bar{2}$	11.72	12.32	—
50 $\bar{4}$	6.22	6.20	—
50 $\bar{6}$	-3.96	-2.52	—
50 $\bar{8}$	3.62	3.96	—
60 $\bar{2}$	3.50	3.96	—
60 $\bar{4}$	7.34	8.76	—
020	-5.52	-6.82	-4.92
040	0	0.24	0.59
060	7.48	7.96	—
011	21.96	29.32	29.40
012	-15.12	-16.64	-16.67

Table 5 (cont.)

hkl	F_o	F_c	F_c^+
013	-7.14	-6.55	-6.46
014	4.00	3.40	—
015	0	1.07	—
016	2.00	1.88	—
017	3.94	3.87	—
021	-12.82	-12.67	-13.34
022	-7.96	-5.93	-7.07
023	-3.06	-3.37	-3.10
024	-4.44	-4.56	-4.21
025	3.86	3.82	—
031	-11.50	-12.54	-12.50
032	0	0.10	0.07
033	-5.20	-5.06	-5.08
034	0	-0.28	—
035	-4.08	-4.41	—
041	4.26	4.01	3.70
042	-3.58	-3.37	-3.63
043	0	0.93	—
044	-4.12	-3.99	—
051	6.78	6.58	—
052	0	0.85	—
053	-3.20	-3.00	—

F_c^+ are the structure factors calculated with the contribution of hydrogen atoms.

The m.s.d. of the bond lengths, calculated from the corresponding deviations of the atomic coordinates given by

$$\sigma(x_{jr}) = \frac{2\pi}{a_j A} \left[\sum_2 h_j^2 \Delta F_j^2 \right]^{1/2} / \sqrt{2p\varrho_0}$$

(Cruickshank, 1949), are 0.010 Å for the N-N bond and 0.007 Å for the C-N bond. The symmetry-related C-N bond distances differ from their average value by 0.011 Å.

The m.s.d. of the bond angles, calculated according to Jeffrey & Parry (1952), is 0.66° for both the N-N-C and N-C-N angles. Symmetry-related bond angles differ from their average by 0.33°.

(f) The molecular arrangement in the lattice and inter-molecular distances

Distances between the nearest atoms belonging to different molecules in the lattice, range between 3.27 Å and 3.67 Å for CH...N contacts, between

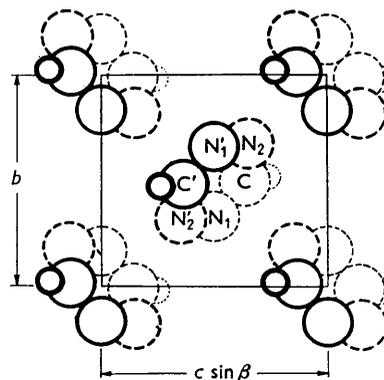


Fig. 4. Packing of the molecules in the unit cell of *s*-tetrazine.

3.41 Å and 3.83 Å for N···N contacts, and between 3.74 Å and 3.79 Å for CH···CH contacts. A drawing of the molecular packing is shown in Fig. 4.

Discussion of the structure

The planarity found for the *s*-tetrazine molecule is consistent with the assumption that nitrogen is sp^2 hybridized in this type of heterocyclic molecule, with one of its *p* electrons taking part in the π bond system of the ring. A molecular orbital calculation gives values of 0.6616 and 0.6618 for the C-N and N-N bond orders respectively, and accounts for the main features of the electronic spectrum of *s*-tetrazine (Liquori & Vaciego, 1956).

While this investigation was being completed accurate determinations of the molecular structure of *s*-triazine (Wheatley, 1955) and phenazine (Herbstein & Schmidt, 1955) have been reported. By plotting the C-N bond distances (*R*) measured in these molecules against the corresponding bond orders (*p*) calculated by the method of molecular orbitals with the same choice of parameters (Davies, 1955; Herbstein & Schmidt, 1955), the relation between these two quantities was found (Liquori & Vaciego, 1956) to be well approximated by the relation

$$R = S - \frac{S - D}{1 + K(1 - p)/p}$$

proposed by Coulson for the C-C bond, where *S* = 1.475 Å is the C-N single-bond distance, and *D* = 1.28 Å is the double-bond distance (Cox & Jeffrey, 1951). The parameter *K* for the C-N bond is found to be 0.6625. A value of 1.329 Å for the C-N bond distance in *s*-tetrazine is calculated from the above relation and compares well with the observed value of 1.334 Å. The deviation of the molecule from a regular hexagon is another interesting feature of the structure of *s*-tetrazine. The C-N-N angle is smaller and the

N-C-N angle is larger than 120° beyond the limits of experimental error and it seems very significant that deviations in the same directions have also been found in the structure of melanine (Hughes, 1941), *s*-triazine and phenazine.

This effect may be ascribed to the hybridization of the lone pair electrons of nitrogen. An approximate theoretical calculation actually shows that the presence of a lone pair in the same sp^2 orbital tends to close the angle between the sp^2 valence orbitals which form the σ bonds in an azine molecule (Hameka & Liquori, 1956). Strains in the whole molecule are therefore probably present which might have some influence upon its physical and chemical properties.

One of us (F. B.) wishes to thank the 'Consiglio Nazionale delle Ricerche' for the award of a Research Fellowship.

References

- BERTINOTTI, F., GIACOMELLO, G. & LIQUORI, A. M. (1954). *Ric. Sci.* **24**, 534.
 BERTINOTTI, F., GIACOMELLO, G. & LIQUORI, A. M. (1955). *Acta Cryst.* **8**, 513.
 COX, E. G., CRUICKSHANK, D. W. J. & SMITH, J. A. S. (1955). *Nature, Lond.* **175**, 766.
 COX, E. G. & JEFFREY, G. A. (1951). *Proc. Roy. Soc. A*, **207**, 110.
 CRUICKSHANK, D. W. J. (1949). *Acta Cryst.* **2**, 65.
 DAVIES, D. W. (1955). *Trans. Faraday Soc.* **51**, 449.
 HAMEKA, H. F. & LIQUORI, A. M. (1956). *Proc. K. Ned. Akad. Wetensch.* In the Press.
 HERBSTEIN, F. H. & SCHMIDT, G. M. J. (1955). *Acta Cryst.* **8**, 399, 406.
 HUGHES, E. W. (1941). *J. Amer. Chem. Soc.* **63**, 1737.
 JEFFREY, G. A. & PARRY, G. S. (1952). *J. Chem. Soc.* p. 4664.
 KARTHA, G. (1953). *Acta Cryst.* **6**, 817.
 LIQUORI, A. M. & VACIEGO, A. (1956). *Ric. Sci.* **26**, 181.
 MCWEENY, R. (1951). *Acta Cryst.* **4**, 513.
 WHEATLEY, P. J. (1955). *Acta Cryst.* **8**, 224.
 WILSON, A. J. C. (1942). *Nature, Lond.* **150**, 152.