

Studies on Flavin Derivatives
The Crystal Structure of 1,3,7,8,10-Pentamethyliso-
alloxazinium Iodide Monohydrate

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The crystal structure of 1,3,7,8,10-pentamethylisoalloxazinium iodide monohydrate, $C_{15}H_{17}N_4O_2I.H_2O$, has been derived from three-dimensional X-ray diffractometer data. The unit cell is orthorhombic, space group $P2_12_12_1$, with the dimensions: $a=12.857 \pm 2$ Å, $b=18.221 \pm 2$ Å, $c=7.049 \pm 2$ Å. There are four formula units in the unit cell.

The structure was determined by the heavy-atom method and all nonhydrogen atoms were given anisotropic temperature factors by full-matrix least-squares refinement. The final R value is 0.047 for 1365 observed reflections.

The ring skeleton of the cation is nearly planar except for a slight departure (7.6°) of the pyrimidine ring from the plane. The iodine atoms are situated between two cations and related to each other by one unit translation along the c axis.

The structure determination of 1,3,7,8,10-pentamethylisoalloxazinium iodide reported here is part of a research program undertaken at this institute to provide three-dimensional structural data of flavin derivatives, particularly of the isoalloxazine ring system in different oxidation states. The prosthetic group of a number of enzymes with redox activity consists of FAD (flavin adenine dinucleotide) or FMN (flavin mononucleotide). During the catalytic process, the isoalloxazine moiety of the coenzyme undergoes one or two electron reductions. In this and previous papers, we have shown that the isoalloxazine ring of simple derivatives of the natural flavin coenzymes is planar in the oxidized state and bent (butterfly configuration) in fully reduced 1,5-dihydroflavin derivatives. Furthermore current X-ray studies of single

* Research Career Development Awardee of the National Institutes of Health (K4-GM-42599).

crystals of flavin radicals should provide the configuration of the flavin in the one-electron reduction state. A preliminary report of the present study has been published earlier.¹

In pentamethylisalloxazinium iodide the alloxazine ring system is positively charged. A schematic structural formula is given in Fig. 1.

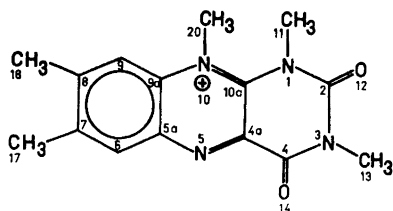


Fig. 1. Schematic drawing of the 1,3,7,8,10-pentamethylisalloxazinium ion.

EXPERIMENTAL

Single crystals of 1,3,7,8,10-pentamethylisalloxazinium iodide, $C_{15}H_{17}N_4O_2I \cdot H_2O$ (cf. Fig. 1) were prepared by one of the authors (F. M.).

Preliminary examinations of the red crystalline specimen by Weissenberg methods indicated orthorhombic symmetry. Systematically absent reflections indicated the space group to be $P2_12_12_1$. Guinier photographs, taken with $CuK\alpha_1$ radiation ($\lambda = 1.54051 \text{ \AA}$) and with KCl ($a = 6.2919 \text{ \AA}$) as an internal standard, were used for determination and least-squares refinement of lattice parameters (Table 1). Calculated and observed values of the composition are given in Table 2.

A prismatic crystal with dimensions $0.07 \times 0.09 \times 0.15 \text{ mm}^3$ was mounted along the c axis, perpendicular to one of the crystal faces.

A total of 1694 unique reflections with θ values below 70° were measured by the $\theta - 2\theta$ scan technique with a Siemens automatic diffractometer equipped with an automatic attenuation filter insertion mechanism, Ni-filtered CuK radiation, and a scintillation counter with pulse height discrimination. Each reflection was measured twice, and stationary background counts were taken at both ends of a scan of range

Table 1. Crystal data.

| | |
|-------------------------|--|
| Lattice constants | $a = 12.857(2) \text{ \AA}$ $b = 18.221(2)$ $c = 7.049(2)$ |
| Cell volume | $V = 1651.4 \text{ \AA}^3$ |
| Density (X-ray) | $d_x = 1.73 \text{ g cm}^{-3}$ |
| Molecules per unit cell | $Z = 4$ |
| Systematic absences | $h00$ for $h = 2n + 1$ $0k0$ for $k = 2n + 1$ $00l$ for $l = 2n + 1$ |
| Space group | $P2_12_12_1$ |

Table 2. Observed and calculated composition of $C_{15}H_{17}N_4O_2I \cdot H_2O$.

| | | | |
|-------------------|--|----------|------------------------------------|
| Calculated values | 41.88 % C 13.02 % N 11.16 % O 4.45 % H 20.49 % I | Analysis | 41.89 % C 12.96 % N 4.52 % H |
|-------------------|--|----------|------------------------------------|

$\Delta\theta = k \tan \theta + l$, where $\Delta\theta_{\pm}$ is the range on each side of the peak. The values of the constants were $l_{+} = 0.30$, $l_{-} = 0.35$, $k_{+} = 0.10$, and $k_{-} = 0.20$.

To keep counting losses low for strong reflections the automatic attenuator was set to add attenuation filters.

Three standard reflections were measured every 24 h; no significant change of intensities was found.

The criterion that the relative error (based on counter statistics) should be less than 0.10 was used to select reflections to be included in the structure refinement. Only the 1365 most significant reflections of the 1694 recorded were used in the subsequent calculations.

The intensities were corrected for Lorentz and polarization effects as well as for absorption. The calculated linear absorption coefficient $\mu = 157 \text{ cm}^{-1}$, led to transmission factors ranging from 0.22 to 0.46. Atomic scattering factors for iodine, and for C, O, and N, were taken from Cromer and Waber³ and from Hanson *et al.*,⁴ respectively. The anomalous dispersion correction for iodine was taken from Cromer.⁵

DETERMINATION AND REFINEMENT OF THE STRUCTURE

The solution of the structure followed a rather straightforward application of the heavy atom method. The first trial position of iodine was determined from the Harker sections. Least-squares refinement of the iodine parameters, first with isotropic then with anisotropic temperature factors, yielded an R -value of 0.29; $R = \sum | |F_{\text{obs}}| - |F_{\text{calc}}| | / \sum |F_{\text{obs}}|$. A Fourier synthesis based on the iodine phases revealed the non-hydrogen atoms forming the three rings. The positional parameters thus obtained for these fourteen atoms were refined together with isotropic temperature factors, initially set to 3 \AA^2 . All atoms were treated as carbon. After five cycles of refinement the R -index was 0.17.

From a subsequent difference electron density map the oxygen and methyl carbon atoms attached to the rings were located and the nitrogen atoms in the rings accordingly identified. Further least-squares refinement lowered the R -value to 0.10. A difference electron density map calculated from the obtained structural parameters revealed the remaining water oxygen. At this stage the anomalous dispersion correction for iodine (+ 6.68) was introduced into the least-squares refinement to determine the absolute configuration. Refinement of the two different enantiomorphs, with an anisotropic temperature factor for iodine and isotropic ones for the nonhydrogen atoms, gave the R -values 0.075 and 0.052, respectively. Hughes' weighting scheme,⁶ $|F|_{\text{obs, min}} = 15.0$, was used throughout all refinements. Since the number of observations is 1365, the number of refined parameters is 98, and the ratio between the obtained weighted R -values (weighted R -value: $R' = [\sum w(|F_{\text{o}}| - |F_{\text{c}}|)^2 / (\sum w |F_{\text{o}}|^2)]^{1/2}$, where w are the individual weights of the observations) for the two enantiomorphs is 1.40, it was concluded that the enantiomorph giving the lowest R -value (0.052) was the correct one (*cf.* Hamilton⁷).

This structure model was then refined by full matrix least-squares with anisotropic temperature factors for all the nonhydrogen atoms, to a final unweighted R -value of 0.047 for all the 1365 reflections. The shifts of the refined parameters in the last cycle were all well below 1 % of their estimated standard deviations (e.s.d.'s). The hypothesis that all atoms but iodine vibrate isotropically can be rejected even at the 0.5 % level of significance, since the ratio between the obtained weighted R -values for the structure model with

Table 3. Fractional atomic coordinates. (The estimated standard deviations are given in parentheses.)

| | <i>x</i> | <i>y</i> | <i>z</i> |
|--------|-------------|-------------|--------------|
| I | 0.81289 (7) | 0.20307 (5) | 0.19847 (12) |
| N(1) | 0.4478 (7) | 0.3280 (4) | 0.2803 (14) |
| C(2) | 0.4306 (10) | 0.4035 (6) | 0.2857 (21) |
| N(3) | 0.3299 (8) | 0.4298 (3) | 0.3105 (24) |
| C(4) | 0.2443 (9) | 0.3858 (6) | 0.3102 (25) |
| C(4a) | 0.2640 (8) | 0.3060 (5) | 0.2992 (18) |
| N(5) | 0.1823 (7) | 0.2633 (4) | 0.2978 (14) |
| C(5a) | 0.1988 (9) | 0.1910 (5) | 0.2926 (18) |
| C(6) | 0.1107 (8) | 0.1437 (6) | 0.2798 (18) |
| C(7) | 0.1246 (9) | 0.0678 (6) | 0.2749 (18) |
| C(8) | 0.2243 (8) | 0.0377 (6) | 0.2947 (19) |
| C(9) | 0.3094 (9) | 0.0837 (5) | 0.3054 (18) |
| C(9a) | 0.2997 (9) | 0.1594 (5) | 0.3097 (17) |
| N(10) | 0.3821 (6) | 0.2079 (5) | 0.3260 (13) |
| C(10a) | 0.3671 (8) | 0.2787 (5) | 0.2969 (17) |
| C(11) | 0.5503 (8) | 0.3073 (6) | 0.1971 (21) |
| O(12) | 0.5021 (7) | 0.4466 (5) | 0.2692 (17) |
| C(13) | 0.3164 (11) | 0.5105 (6) | 0.3239 (23) |
| O(14) | 0.1578 (6) | 0.4116 (5) | 0.3177 (20) |
| C(17) | 0.0312 (9) | 0.0183 (7) | 0.2548 (21) |
| C(18) | 0.2413 (10) | -0.0440 (6) | 0.2988 (21) |
| C(20) | 0.4808 (10) | 0.1764 (7) | 0.4020 (22) |
| O(w) | 0.4890 (9) | 0.1546 (5) | 0.9361 (18) |

Table 4. Anisotropic thermal parameters. The estimated standard deviations are given in parentheses. The temperature factor expression used is $\exp[-(h^2b_{11} + k^2b_{22} + l^2b_{33} + hkb_{12} + hlb_{13} + klb_{23})]$.

| | $b_{11} \times 10^4$ | $b_{22} \times 10^4$ | $b_{33} \times 10^4$ | $b_{12} \times 10^4$ | $b_{13} \times 10^4$ | $b_{23} \times 10^4$ |
|--------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|
| I | 49.0 (5) | 45.9 (3) | 180.8 (14) | 5.1 (8) | -3.9 (20) | -9.1 (15) |
| N(1) | 31 (6) | 26 (3) | 173 (19) | -3 (6) | 14 (21) | -2 (13) |
| C(2) | 47 (8) | 26 (4) | 199 (26) | 0 (9) | -9 (32) | -4 (20) |
| N(3) | 55 (8) | 24 (3) | 243 (24) | 7 (7) | -36 (31) | 0 (16) |
| C(4) | 34 (8) | 29 (4) | 218 (27) | 2 (8) | -12 (33) | 0 (22) |
| C(4a) | 34 (7) | 19 (3) | 160 (19) | 2 (7) | -8 (24) | -2 (19) |
| N(5) | 38 (6) | 30 (3) | 158 (17) | 10 (7) | 34 (29) | 4 (14) |
| C(5a) | 43 (8) | 24 (4) | 126 (17) | 4 (8) | 16 (28) | 11 (17) |
| C(6) | 40 (7) | 29 (4) | 144 (23) | -22 (8) | 44 (24) | 1 (17) |
| C(7) | 41 (8) | 30 (4) | 158 (26) | -10 (8) | 16 (25) | 5 (17) |
| C(8) | 39 (8) | 26 (3) | 128 (19) | -2 (7) | -13 (25) | 0 (18) |
| C(9) | 40 (7) | 26 (3) | 153 (20) | 15 (8) | 22 (39) | -12 (17) |
| C(9a) | 40 (8) | 28 (3) | 115 (19) | 12 (8) | 29 (30) | 9 (16) |
| N(10) | 32 (6) | 28 (3) | 136 (18) | 0 (7) | 8 (18) | 18 (15) |
| C(10a) | 39 (8) | 21 (4) | 126 (19) | 1 (7) | 22 (24) | -4 (16) |
| C(11) | 33 (8) | 34 (4) | 285 (28) | -2 (8) | 61 (30) | 74 (24) |
| O(12) | 50 (6) | 33 (3) | 393 (31) | -18 (6) | 16 (21) | -11 (16) |
| C(13) | 71 (9) | 23 (3) | 344 (39) | 3 (10) | -35 (55) | -11 (21) |
| O(14) | 39 (6) | 34 (3) | 434 (33) | 11 (6) | -10 (26) | 3 (20) |
| C(17) | 37 (8) | 33 (4) | 352 (48) | -16 (9) | -5 (29) | -18 (21) |
| C(18) | 60 (9) | 24 (3) | 215 (26) | -9 (9) | 0 (34) | -12 (21) |
| C(20) | 29 (8) | 32 (4) | 290 (33) | 12 (8) | -74 (30) | 36 (20) |
| O(w) | 91 (8) | 39 (4) | 395 (33) | -3 (9) | 71 (29) | -16 (18) |

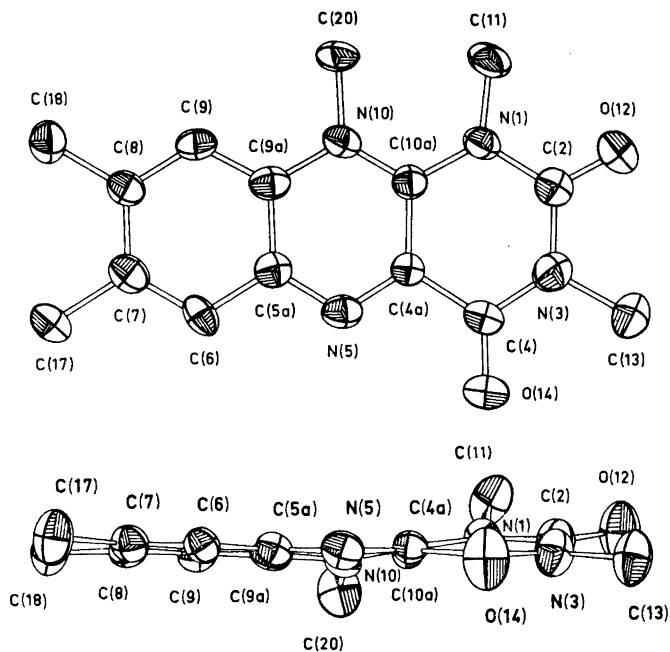


Fig. 2. Molecular conformation observed in the crystal structure of 1,3,7,8,10-pentamethylisoalloxazinium iodide monohydrate with atoms numbered for reference in the text, and anisotropic thermal ellipsoids of the nonhydrogen atoms.

Table 6. Intramolecular bond distances. The estimated standard deviations are given in parentheses.

| | |
|--------------|--------------|
| N(1)–C(2) | 1.395 (13) Å |
| C(2)–N(3) | 1.391 (16) |
| N(3)–C(4) | 1.361 (15) |
| C(4)–C(4a) | 1.479 (15) |
| C(4a)–N(5) | 1.307 (14) |
| N(5)–C(5a) | 1.334 (13) |
| C(5a)–C(6) | 1.426 (15) |
| C(6)–C(7) | 1.394 (15) |
| C(7)–C(8) | 1.402 (16) |
| C(8)–C(9) | 1.380 (15) |
| C(9)–C(9a) | 1.385 (14) |
| C(9a)–N(10) | 1.384 (14) |
| N(10)–C(10a) | 1.320 (13) |
| C(10a)–N(1) | 1.377 (13) |
| C(4a)–C(10a) | 1.415 (15) |
| C(5a)–C(9a) | 1.425 (16) |
| N(1)–C(11) | 1.491 (14) |
| C(2)–O(12) | 1.214 (15) |
| N(3)–C(13) | 1.483 (14) |
| C(4)–O(14) | 1.210 (14) |
| C(7)–C(17) | 1.509 (16) |
| C(8)–C(18) | 1.505 (15) |
| N(10)–C(20) | 1.492 (15) |

Table 7. Intramolecular bond angles in degrees. Estimated standard deviations are given in parentheses.

| | |
|--------------------|------------|
| C(10a)–N(1)–C(2) | 121.4 (9) |
| C(10a)–N(1)–C(11) | 122.4 (8) |
| C(11)–N(1)–C(2) | 113.6 (9) |
| N(1)–C(2)–N(3) | 119.4 (10) |
| N(1)–C(2)–O(12) | 121.0 (11) |
| O(12)–C(2)–N(3) | 119.6 (10) |
| C(2)–N(3)–C(4) | 123.3 (9) |
| C(2)–N(3)–C(13) | 117.3 (10) |
| C(13)–N(3)–C(4) | 119.3 (10) |
| N(3)–C(4)–C(4a) | 116.2 (10) |
| N(3)–C(4)–O(14) | 121.0 (10) |
| O(14)–C(4)–C(4a) | 122.8 (11) |
| C(4)–C(4a)–N(5) | 116.6 (9) |
| C(4)–C(4a)–C(10a) | 120.4 (9) |
| C(10a)–C(4a)–N(5) | 123.0 (9) |
| C(4a)–N(5)–C(5a) | 117.3 (10) |
| N(5)–C(5a)–C(6) | 118.2 (10) |
| N(5)–C(5a)–C(9a) | 122.8 (10) |
| C(9a)–C(5a)–C(6) | 119.0 (9) |
| C(5a)–C(6)–C(7) | 120.0 (10) |
| C(6)–C(7)–C(8) | 120.1 (10) |
| C(6)–C(7)–C(17) | 119.6 (10) |
| C(17)–C(7)–C(8) | 120.2 (10) |
| C(7)–C(8)–C(9) | 119.5 (10) |
| C(7)–C(8)–C(18) | 121.4 (10) |
| C(18)–C(8)–C(9) | 119.0 (10) |
| C(8)–C(9)–C(9a) | 122.3 (11) |
| C(9)–C(9a)–N(10) | 124.7 (10) |
| C(9)–C(9a)–C(5a) | 118.8 (10) |
| C(5a)–C(9a)–N(10) | 116.5 (9) |
| C(9a)–N(10)–C(10a) | 120.0 (9) |
| C(9a)–N(10)–C(20) | 115.7 (9) |
| C(20)–N(10)–C(10a) | 123.8 (9) |
| N(10)–C(10a)–N(1) | 122.6 (9) |
| N(10)–C(10a)–C(4a) | 118.5 (9) |
| C(4a)–C(10a)–N(1) | 118.6 (8) |

DISCUSSION OF THE CRYSTAL AND MOLECULAR STRUCTURE

The crystal structure, viewed along the a and c axes, is shown in Figs. 3 and 4. As seen in Fig. 3, the c axis is nearly perpendicular to the molecular planes of the alloxazinium ions. The iodine atoms, situated between two alloxazinium ions, are related to each other by one unit translation along the c axis, in the stacking sequence ...alloxazinium–iodide–alloxazinium–iodide... along z . Fairly short contact distances, 3.57 and 3.58 Å, occur between iodine and the two carbon atoms C(4a) and C(10a) of the alloxazinium ring. The molecular stacking, the short contact distances, and the deep red colour of the crystals suggest charge transfer interactions between the iodide and the alloxazinium ions to yield an axial charge transfer complex (*cf.* Mulliken and Pearson⁸). The formation of charge transfer complexes in solution between isoalloxazines, as well as alloxazines, and a variety of donor molecules has been demonstrated spectrophotometrically (Fleischman and Tollin,⁹ and Ray

Table 8. Intermolecular distances less than 3.6 Å. Estimated standard deviations are given in parentheses.

| Code for symmetry related atoms Superscript | Atom at | Superscript | Atom at |
|--|--|-------------|---|
| None | x, y, z | v | $\frac{1}{2}-x, \bar{y}, \frac{1}{2}+z$ |
| i | $\frac{1}{2}+x, \frac{1}{2}-y, \bar{z}$ | vi | $1-x, -\frac{1}{2}+y, \frac{1}{2}-z$ |
| ii | $\frac{1}{2}+x, \frac{1}{2}-y, 1-z$ | vii | $x, y, -1+z$ |
| iii | $-\frac{1}{2}+x, \frac{1}{2}-y, 1-z$ | viii | $1-x, \frac{1}{2}+y, \frac{1}{2}-z$ |
| iv | $\frac{1}{2}-x, \bar{y}, -\frac{1}{2}+z$ | ix | $\bar{x}, \frac{1}{2}+y, \frac{1}{2}-z$ |
| I-C(4a i) | | | 3.568 (12) Å |
| I-C(10a i) | | | 3.576 (12) |
| I-O(w ii) | | | 3.571 (11) |
| N(5)-C(20 iii) | | | 3.522 (16) |
| N(5)-O(w iii) | | | 3.336 (15) |
| C(6)-C(11 i) | | | 3.564 (19) |
| C(7)-O(12 ii) | | | 3.589 (17) |
| C(8)-C(18 iv) | | | 3.526 (20) |
| C(8)-C(18 v) | | | 3.582 (20) |
| C(9)-O(12 vi) | | | 3.520 (14) |
| C(9a)-O(w vii) | | | 3.587 (17) |
| N(10)-O(w vii) | | | 3.223 (15) |
| C(11)-O(w vii) | | | 3.427 (16) |
| O(12)-C(17 ii) | | | 3.436 (19) |
| O(12)-C(18 viii) | | | 3.339 (15) |
| O(14)-C(17 ix) | | | 3.152 (15) |
| O(14)-C(20 iii) | | | 3.414 (17) |
| O(14)-O(w iii) | | | 3.060 (16) |
| C(17)-O(w iv) | | | 3.410 (16) |
| C(20)-O(w vii) | | | 3.310 (20) |

Table 9. Computer programs used for the crystallographic calculations.

| Program name and function | Authors |
|---|--|
| SIP. Generation of steering paper tape for the SIEMENS AED. | Norrestam, R. |
| SIMSA. Interpretation of output on paper tape from the SIEMENS AED and evaluation of intensities. | Norrestam, R. |
| DATAP 2. Lp- and absorption corrections. Preparative calculations for extinction correction. | Coppens, P., Leiserowitz, L. & Rabinovich., Modified by Olofsson, O. Elfström, M., Brandt, B., Åsbrink, S. & Nord, A. |
| DATA. Reflection data handling. | Brandt, B. |
| DRF. Fourier summations and structure factor calculations. | Zalkin, A. Modified by Liminga, R., Lundgren, J. O., Brandt, B. & Nord, A. |
| LALS. Full matrix least-squares refinement of positional and thermal parameters and of scale factors. | Gantzel, P. K., Sparks, R. A. & Trueblood, K. N. Modified by Zalkin, A., Lundgren, J. O., Liminga, R., Brändén, C.-I., Lindgren, O., Brandt, B. & Nord, A. |
| DISTAN. Calculation of interatomic distances and bond angles with estimated standard deviations. | Zalkin, A. Modified by Nord, A. & Brandt, B. |

Table 1. Continued.

| | |
|--|--|
| INERT. Calculation of least squares plane and axes of inertia. | Norrestam, R. |
| ORTEP. Thermal-ellipsoid plot for crystal structure illustrations. | Johnson, C. K. Modified by Carlbom, I. |
| TORSO. Calculation of torsion angles. | Norrestam, R. |
| ACTA. Editing of structure factor tables. | Norrestam, R. |

*et al.*¹⁰ Furthermore, Matsunaga¹¹ has shown that, *e.g.*, dimethylalloxazine can act as an acceptor as well as a donor. However, the shortest distances between the iodide and the alloxazinium ions are about 3.6 Å, whereas the sum of the van der Waals radii is 3.7–3.9 Å (Pauling¹² and Bondi¹³). Thus, the possible charge transfer interactions must be rather weak.

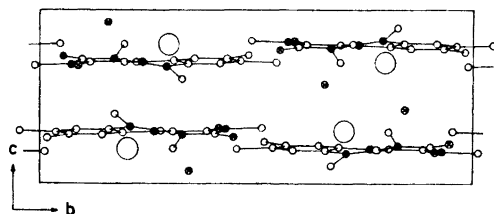


Fig. 3. The structure viewed along the *a* axis. The large open circles denote iodine atoms, small open circles carbon atoms, solid circles nitrogen atoms, and circled crosses oxygen atoms.

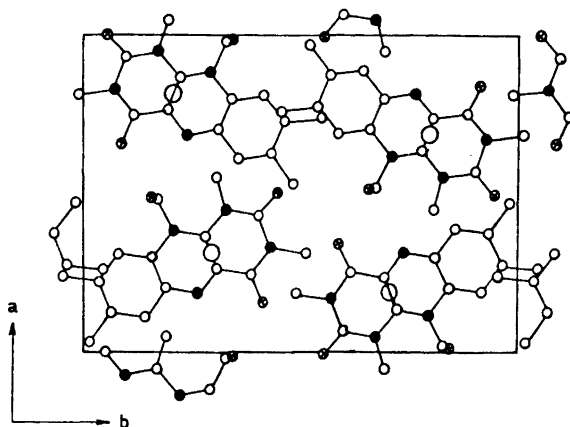
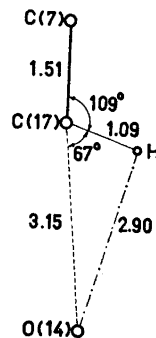


Fig. 4. The structure viewed along the *c* axis. The large open circles denote iodine atoms, small open circles carbon atoms, solid circles nitrogen atoms, and circled crosses oxygen atoms.

The water molecule in the crystal structure forms a short contact with an iodide ion, 3.57 Å, in good agreement with the oxygen–iodide distance 3.53 Å reported by Clark¹⁴ as the average value of O–H...I⁻ hydrogen bond distances calculated from five organic hydrates. The water molecule seems not to form any other particularly strong hydrogen bonds. The shortest distances to the water oxygen occur from O(14), 3.06 Å, from N(10), 3.22 Å, and from N(5), 3.34 Å (*cf.* Table 6). Hamilton and Ibers¹⁵ give the expected values 2.8 and 2.9 Å as normal O–H...O and O–H...N hydrogen bond distances. However, since reliable hydrogen positions could not be obtained, the existence of further hydrogen bonds in the structure cannot be excluded. The angles I⁻...O(w)...O(14), I⁻...O(w)...N(10), and I⁻...O(w)...N(5) of 125.5°, 74.8°, and 90.9°, show that there are possibilities of approximately linear hydrogen bonds from the water molecule to one or both of O(14) and N(10).

Among the nonhydrogen atoms of the alloxazinium ions, there is one intermolecular contact distance which is considerably shorter than the sum of the van der Waals radii, *viz.* between C(17) of one alloxazinium molecule and O(14) of another one. This distance is 3.15 Å, compared to the sum, about 3.40 Å, of the van der Waals radii. The interpretation of such short contacts between carbon and oxygen has been discussed frequently. Sutor¹⁶ suggested that such interactions might indicate weak hydrogen bonds. The evidence she adduced has been contested by Donohue.¹⁷ However, short C–H...O contacts (Sundaralingam¹⁸) play a role in the stabilization of certain molecular conformations. In the present structure there is no C–H...O contact indicating hydrogen bonds. Assuming normal geometry of the methyl groups, the distances between the hydrogens of the methyl group at C(17) and the oxygen O(14) of another molecule must all be larger than about 2.9 Å, as shown in Fig. 5. The sum of the corresponding van der Waals radii is about 2.6 Å. In the present case the methyl carbon C(17) probably has a small positive charge, while the keto oxygen O(14) has a negative charge. This suggests that a molecular packing leading to the observed short C(17)...O(14) contact might still be electrostatically favorable.

Fig. 5. The short contact between C(17) and O(14 ix) (*cf.* Table 8 and text). As indicated in the figure the shortest possible distance between any of the hydrogens attached to the methyl carbon C(17) and the oxygen atom O(14) is about 2.9 Å if normal geometry of the methyl group is assumed (*i.e.* C–H bond distances of 1.09 Å and bond angles of about 109°).



As shown in Fig. 3, the alloxazine ring system of the cations are essentially planar (*cf.* Table 10). However, the pyrimidinoid ring is slightly twisted out

Table 10. Deviations of the atoms from least-squares planes. The planes are defined by $AX + BY + CZ = D$, where X , Y , and Z in Ångströms along the axes a , b , and c . The atoms indicated with asterisks were omitted from the calculations of the least-squares planes.

| Plane I | | | Plane II | | |
|--------------|--------|-----------|--|--------|-----------|
| | Atom | Deviation | | Atom | Deviation |
| A = -0.0210 | N(1) | -0.168 Å | A = 0.0676 | N(1) | -0.019 Å |
| B = -0.0012 | C(2) | -0.127 | B = -0.0249 | C(2) | -0.029 |
| C = 0.9998 | N(3) | 0.074 | C = 0.9974 | N(3) | 0.045 |
| D = 2.0151 Å | C(4) | 0.096 | D = 2.2293 Å | C(4) | -0.012 |
| | C(4a) | 0.015 | | C(4a) | -0.036 |
| | N(5) | 0.028 | | C(10a) | 0.050 |
| | C(5a) | -0.011 | | *C(11) | -0.505 |
| | C(6) | -0.076 | | *O(12) | -0.104 |
| | C(7) | -0.113 | | *C(13) | 0.091 |
| | C(8) | 0.001 | | *O(14) | -0.046 |
| | C(9) | 0.052 | | *N(5) | -0.097 |
| | C(9a) | 0.083 | | *N(10) | 0.300 |
| | N(10) | 0.174 | The e.s.d. of the atoms without asterisks from the plane is 0.049 Å. | | |
| | C(10a) | -0.028 | | | |
| | *C(11) | -0.782 | | | |
| | *O(12) | -0.264 | | | |
| | *C(13) | 0.170 | | | |
| | *O(14) | 0.172 | | | |
| | *C(17) | -0.228 | | | |
| | *C(18) | 0.026 | | | |
| | *C(20) | 0.684 | | | |

The e.s.d. of the atoms without asterisks from the plane is 0.104 Å.

| Plane III | | | Plane IV | | |
|--------------|--------|-----------|--|--------|-----------|
| | Atom | Deviation | | Atom | Deviation |
| A = -0.0520 | C(4a) | 0.021 Å | A = -0.0866 | C(5a) | -0.008 Å |
| B = 0.0308 | N(5) | 0.041 | B = -0.0142 | C(6) | 0.013 |
| C = 0.9982 | C(5a) | -0.047 | C = 0.9961 | C(7) | -0.018 |
| D = 2.0799 Å | C(9a) | -0.011 | D = 1.7917 Å | C(8) | 0.018 |
| | N(10) | 0.075 | | C(9) | -0.014 |
| | C(10a) | -0.080 | | C(9a) | 0.008 |
| | *N(1) | -0.223 | | *N(10) | 0.018 |
| | *C(4) | 0.156 | | *N(5) | 0.028 |
| | *C(6) | -0.104 | | *C(17) | -0.042 |
| | *C(9) | -0.091 | | *C(18) | 0.049 |
| | *C(20) | 0.526 | The e.s.d. of the atoms without asterisks from the plane is 0.020 Å. | | |

The e.s.d. of the atoms without asterisks from the plane is 0.074 Å.

of the molecular plane by a rotation perpendicular to the C(4a)–C(10a) bond around an axis in the long direction of the alloxazine ring system. The torsion angle across the C(4a)–C(10a) bond, defined by the atoms C(4)–C(4a)–C(10a)–N(10), becomes 166.4°. Calculations of least-squares planes through the three six-membered rings forming the alloxazine ring system indicate that the benzenoid ring is the most planar and the pyrazinoid ring the least of the three rings. The angle between the normals of the benzenoid and pyrazinoid least-squares planes is 3.3°, while that between the normals of the pyrazinoid and pyrimidinoid planes is 7.6°. The observed twist of the pyrimidinoid ring out of the molecular plane is probably due to repulsion forces between the methyl groups substituted to N(1) and N(10), the distance between

methyl carbons C(11) and C(20) is increased to 2.93 Å, which agrees well with the distance 2.95 Å between methyl carbons C(17) and C(18) attached to the benzenoid ring.

The bond lengths and angles within the alloxazinium ion are listed in Tables 6 and 7. In the benzenoid ring the carbon-carbon distances vary between 1.380 and 1.426, which agree with the common benzenoid value 1.396 Å to within twice the estimated standard deviations. The magnitude of the e.s.d.'s, about 0.015 Å, of the carbon-carbon distances in the benzenoid ring do not permit reliable description of the distribution of the length differences within this ring. The distances C(7)-C(17) and C(8)-C(18), 1.509 and 1.505 Å, respectively, are close to the value 1.52 Å for C(sp³)-C(sp²) distances found, *e.g.*, in toluene. The bond angles within the benzenoid ring are all within twice their e.s.d.'s from the trigonal value 120°.

To judge from their lengths, all the bonds within the pyrazinoid and pyrimidinoid rings have some double bond character. The distribution of the bond lengths is consonant with the schematic bond scheme shown in Fig. 1. Thus the distances C(4a)-N(5) and N(10)-C(10a), 1.307 and 1.320 Å, are fairly close to the value 1.28 Å expected for pure C-N double bonds. The fairly short C(4a)-C(10a) distance (1.415 Å) suggests positive charges not only for the nitrogen N(10) (as indicated in Fig. 1) but also for carbon atoms C(4a) and C(10a). From a simple electrostatic point of view, such a charge distribution is in accordance with the observed molecular packing of the crystal structure characterized by short contact distances between the iodide ion and carbon atoms C(4a) and C(10a).

Table 11. Comparison of bond distances within the 1,3,7,8,10-pentamethylisalloxazinium and 10-methylisalloxazinium ions. The estimated standard deviations are given in parentheses.

| | 1,3,7,8,10- pentamethyliso- alloxazinium | 10-methyliso- alloxazinium |
|--------------|--|-------------------------------|
| N(1)-C(2) | 1.395 (13) Å | 1.408 (7) Å |
| C(2)-N(3) | 1.391 (16) | 1.379 (7) |
| N(3)-C(4) | 1.361 (15) | 1.388 (7) |
| C(4)-C(4a) | 1.479 (15) | 1.489 (7) |
| C(4a)-N(5) | 1.307 (14) | 1.299 (7) |
| N(5)-C(5a) | 1.334 (13) | 1.376 (7) |
| C(5a)-C(6) | 1.426 (15) | 1.411 (7) |
| C(6)-C(7) | 1.394 (15) | 1.348 (7) |
| C(7)-C(8) | 1.402 (16) | 1.415 (7) |
| C(8)-C(9) | 1.380 (15) | 1.362 (7) |
| C(9)-C(9a) | 1.385 (14) | 1.419 (7) |
| C(9a)-N(10) | 1.384 (14) | 1.386 (7) |
| N(10)-C(10a) | 1.320 (13) | 1.338 (7) |
| C(10a)-N(1) | 1.377 (13) | 1.364 (7) |
| C(4a)-C(10a) | 1.415 (15) | 1.422 (7) |
| C(5a)-C(9a) | 1.425 (16) | 1.407 (7) |
| C(2)-O(12) | 1.214 (15) | 1.209 (7) |
| C(4)-O(14) | 1.210 (14) | 1.211 (7) |

The carbon–oxygen distances C(2)–O(12) and C(4)–O(14), 1.214 and 1.210 Å, establish that both of these oxygens attached to the pyrimidinoid ring are of keto type.

The exocyclic carbon–nitrogen bond distances, ranging from 1.48 to 1.49 Å, establish that these bonds are of pure single character.

The agreement between the intramolecular bond distances found in the present study and those obtained by Trus and Fritchie¹⁹ from the crystal structure determination of 10-methyl-isoalloxazinium bromide dihydrate is satisfactory (Table 11). The largest bond length differences, for the N(5)–C(5a) and the C(6)–C(7) bonds, just exceed three e.s.d.'s. Since no corrections of the bond lengths for thermal vibrations have been performed in either of the two structure determinations, the observed bond length differences are too small to permit any reliable conclusions regarding the effects of the possible charge transfer interactions.

Acknowledgements. This investigation has been performed within a research program directed by Professor Peder Kierkegaard with financial support from the *Tri-Centennial Fund of the Bank of Sweden* and from the *Swedish Natural Science Research Council*. Permission for the use of the computers CD 3600 and IBM 360/75 was granted by the *Computer Division of the National Swedish Rationalization Agency*.

The authors are indebted to Professor Peder Kierkegaard for his stimulating interest in this work. Thanks are also due to Professor Arne Magnéli for all facilities placed at their disposal and to Professor Inga Fischer-Hjalmars for stimulating discussions. The authors are indebted to Dr. Don Koenig for correction of the English of this paper.

A research fellowship from the *Stiftelsen Bengt Lundqvists Minne* to one of us (R.N.) is gratefully acknowledged.

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Received November 1, 1971.