

(C₆H₄SNH)Fe₂(CO)₆ tient à la disproportion, dans le double pont mixte, des rayons covalents respectifs du soufre et de l'azote. Ceci semblerait indiquer que, au-dessous d'une certaine valeur de la distance X-X', et dans le cas où X et X' ne sont pas directement liés, une forte liaison Fe-Fe puisse s'établir. L'origine de cette forte liaison serait par conséquent peut-être due plus à des effets stériques qu'à des transferts électroniques en retour des atomes métalliques vers les atomes ponteurs.

Nous remercions Monsieur le Professeur R. Dabard (Laboratoire de Chimie Organique E, Université de Rennes I) qui nous a accueillis dans son laboratoire et conseillés lors de la synthèse du présent complexe et d'autres dérivés du fer carbonyle.

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The Crystal and Molecular Structure of a Dimeric Piperidone Condensation Product*

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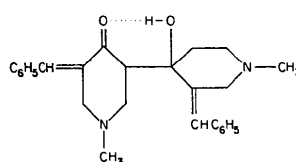
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The condensation reaction under basic conditions between 1-methyl-4-piperidone and *p*-bromobenzaldehyde gives a dimeric product C₂₆H₂₈N₂O₂Br₂, the structure of which has been established by X-ray analysis as 4-*p*-bromobenzylidene-9-*p*-bromophenyl-10a-hydroxy-2,7-dimethyl-2,7-diaza-10-oxa-1,2,3,4,5,6,7,8,8a,10a-decahydroanthracene. The compound crystallizes as the monohydrate in space group *Pbca*, with lattice dimensions *a* = 11.530 (5), *b* = 8.399 (5), *c* = 52.930 (3) Å. There are 8 dimer molecules and 8 water molecules of crystallization in the unit cell, and the observed and calculated densities are 1.500 and 1.499 g cm⁻³ respectively. The structure was solved by the heavy-atom method with diffractometer data, and refined using the block-diagonal least-squares procedure to a final *R* value of 0.081 for 3072 observed reflexions. The ring system of the central portion of the molecule with the symmetric pattern of hetero-atoms is unusual. The fully saturated ring junction is *trans*, and the three heterocyclic rings have chair, half-chair and sofa conformations. One phenyl group is nearly perpendicular to the central tricyclic system, while the aromatic ring of the benzylidene group is twisted about 33° from coplanarity with the adjacent conjugated double bond system. Dimer molecules are hydrogen bonded alternately with water molecules into chains along *b*, which are separated from each other by van der Waals contact distances.

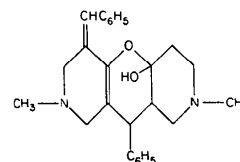
Introduction

McElvain & Parker (1955) proposed structure (I) for the dimeric product of the condensation reaction between benzaldehyde and 1-methyl-4-piperidone under basic conditions. Mass spectral data were not entirely consistent with this model and n.m.r. data were inconclusive (Lyle, Dziark, Connor & Huber, 1973);

consequently an X-ray analysis was undertaken and showed that the dimer structure is (II).



(I)



(II)

* Issued as NRCC No. 13123.

Experimental

Crystals of the *p*-bromo derivative of the dimer occur as thin, colourless plates, somewhat elongated parallel to the *b* axis. Most of the specimens which were examined could be seen microscopically to consist of two or more individuals, rotated slightly about the normal to the plate face. Even those which appeared single generally gave multiple X-ray reflexions with an angular range of several degrees. Attempts to improve the quality of the crystals by recrystallization were unsuccessful. Finally a specimen was found which was essentially a single crystal, with only one small satellite about $\frac{1}{6}$ of the volume of the main component. Although the crystal shape was unfortunately rather irregular, it was mounted on a Picker diffractometer with its *b* axis parallel to ϕ . Maximum crystal dimensions (parallel to **a**, **b**, **c**) were $0.20 \times 0.56 \times 0.11$ mm.

Crystal data

$C_{26}H_{28}N_2O_2Br_2 \cdot H_2O$ F.W. 578.4

Orthorhombic, space group *Pbca*

$a = 11.530$ (5), $b = 8.399$ (5), $c = 52.930$ (3) Å

$V = 5125.7$ Å³ [$\lambda(\text{Cu } K\alpha_1) = 1.54051$ Å and

$\lambda(\text{Cu } K\alpha_2) = 1.54433$ Å]

$D_m = 1.500$ g cm⁻³ (by flotation in mixed solvents)

$D_x = 1.499$ g cm⁻³, $Z = 8$, $F(000) = 2352$

Linear absorption coefficient $\mu(\text{Cu } K\alpha) = 47.0$ cm⁻¹.

Systematic absences, deduced from precession photographs, were *hk0* if *h* is odd, *0kl* if *k* is odd, *h0l* if *l* is odd. Together with the orthorhombic lattice symmetry these suggested space group *Pbca*.

Cell dimensions and relative intensities were measured at room temperature with Ni-filtered Cu radiation and pulse-height discrimination. Cell dimensions were obtained from 2θ values of high-angle axial reflexions, measured with a small take-off angle and narrow detector slit. The intensity data were collected using $\theta/2\theta$ scans, and accumulating background counts for 20 sec at the beginning and end of each scan. The scan ranges were 2° (in 2θ) for $0 < 2\theta \leq 60^\circ$, 3° for $60^\circ < 2\theta \leq 100^\circ$, and 4° for $100^\circ < 2\theta \leq 130^\circ$, and the scan speed was 2° min^{-1} . Very strong intensities were remeasured with reduced X-ray tube current. One octant of reciprocal space was surveyed and 3075 reflexions of the 4348 scanned had net counts above threshold. The threshold level was defined as 10% of the total background count or a net count of 100, whichever was greater. Reflexions considered 'unobserved' were excluded from the least-squares refinement but were included in the final structure factor calculation. A standard reflexion (0,0,20) was measured after every 30–40 reflexions, and these measurements were used to scale the data. The intensity of the standard reflexion had decreased by about 12% at the end of the data collection. However, because of the

Table 1. Final parameters for the non-hydrogen atoms

All U_{ij} 's are $\times 10^4$. Temperature factors are of the form $T = \exp[-2\pi^2(U_{11}h^2a^{*2} + \dots + 2U_{23}klb^*c^* + \dots)]$.

	<i>x</i> ($\times 10^4$)	<i>y</i> ($\times 10^4$)	<i>z</i> ($\times 10^5$)	U_{11}	U_{22}	U_{33}	$2U_{23}$	$2U_{13}$	$2U_{12}$
C(1)	903 (7)	3468 (9)	37084 (15)	565 (49)	318 (40)	397 (43)	43 (68)	65 (71)	-68 (74)
N(2)	580 (5)	3759 (7)	34462 (12)	419 (34)	227 (30)	454 (43)	41 (50)	189 (56)	40 (51)
C(3)	1166 (7)	2608 (10)	32823 (14)	442 (42)	422 (44)	383 (43)	97 (70)	167 (68)	10 (73)
C(4)	781 (6)	963 (9)	33429 (13)	342 (36)	366 (40)	298 (43)	47 (63)	56 (59)	169 (65)
C(4a)	492 (6)	684 (9)	36074 (13)	286 (34)	408 (41)	355 (43)	-79 (65)	-96 (65)	-17 (62)
C(5)	-816 (7)	-2719 (9)	39208 (14)	460 (42)	297 (40)	355 (43)	65 (61)	15 (65)	42 (68)
C(6)	-1460 (6)	-2984 (9)	41689 (15)	344 (39)	399 (43)	483 (43)	68 (72)	204 (68)	-172 (67)
N(7)	-824 (5)	-2291 (8)	43782 (11)	405 (34)	523 (40)	312 (28)	108 (59)	77 (53)	-86 (62)
C(8)	-688 (6)	-584 (9)	43422 (13)	391 (39)	337 (40)	312 (43)	38 (61)	31 (62)	22 (65)
C(8a)	-32 (6)	-237 (8)	41009 (13)	262 (34)	237 (34)	412 (43)	68 (59)	-65 (59)	-31 (57)
C(9)	166 (6)	1575 (9)	40551 (13)	355 (38)	335 (39)	355 (43)	-108 (63)	-37 (62)	122 (64)
C(9a)	566 (6)	1804 (8)	37842 (14)	285 (35)	202 (33)	426 (43)	146 (61)	6 (59)	38 (56)
O(10)	94 (4)	-840 (5)	36568 (9)	449 (28)	233 (24)	412 (28)	20 (43)	210 (43)	-108 (44)
C(10a)	-636 (6)	-966 (8)	38749 (12)	300 (34)	295 (36)	284 (28)	36 (56)	62 (56)	-130 (59)
C(11)	896 (8)	5394 (9)	33683 (17)	615 (53)	353 (44)	511 (43)	106 (74)	278 (83)	-71 (80)
C(12)	-1426 (8)	-2626 (12)	46142 (18)	613 (56)	679 (61)	497 (57)	119 (92)	229 (87)	-174 (99)
O(13)	-1674 (4)	-147 (6)	38302 (10)	333 (26)	407 (29)	511 (28)	-52 (50)	-130 (46)	53 (46)
C(14)	658 (7)	-230 (9)	31761 (15)	411 (42)	418 (44)	412 (43)	54 (70)	-6 (68)	117 (71)
C(15)	944 (7)	-244 (10)	29017 (15)	556 (50)	423 (45)	397 (43)	-14 (72)	-99 (74)	250 (80)
C(16)	1856 (7)	590 (10)	27913 (15)	500 (48)	435 (47)	412 (43)	-47 (72)	0 (71)	64 (77)
C(17)	2087 (8)	429 (13)	25376 (17)	571 (56)	795 (68)	468 (57)	-9 (95)	83 (83)	100 (101)
C(18)	1425 (9)	-561 (13)	23871 (17)	619 (57)	878 (73)	383 (43)	-144 (92)	176 (83)	261 (108)
C(19)	504 (9)	-1404 (15)	24902 (20)	639 (61)	1057 (84)	539 (57)	-608 (122)	-25 (96)	-278 (117)
C(20)	285 (9)	-1252 (12)	27442 (19)	578 (55)	698 (65)	582 (57)	-261 (97)	266 (90)	-169 (100)
C(21)	970 (7)	2264 (8)	42522 (14)	478 (43)	236 (37)	383 (43)	56 (61)	22 (68)	-163 (65)
C(22)	519 (7)	3177 (10)	44478 (16)	412 (44)	446 (46)	511 (43)	-234 (79)	108 (74)	-59 (75)
C(23)	1237 (8)	3727 (10)	46428 (16)	587 (53)	393 (46)	468 (43)	-162 (74)	142 (80)	-145 (78)
C(24)	2390 (8)	3338 (11)	46332 (14)	589 (51)	530 (51)	355 (43)	-18 (77)	-74 (74)	-483 (86)
C(25)	2864 (7)	2457 (10)	44429 (15)	424 (42)	522 (48)	426 (43)	140 (79)	-145 (71)	-269 (79)
C(26)	2149 (6)	1933 (10)	42558 (15)	362 (40)	479 (47)	397 (43)	140 (72)	124 (65)	-183 (72)
O(27)	-1840 (5)	3026 (7)	35554 (13)	425 (32)	534 (37)	781 (43)	257 (65)	356 (59)	268 (55)
Br(1)	1795 (1)	-825 (2)	20433 (2)	974 (9)	1690 (15)	369 (14)	-378 (16)	114 (12)	58 (20)
Br(2)	3372 (1)	4110 (2)	48996 (2)	749 (7)	1122 (9)	383 (14)	-153 (11)	-136 (9)	-824 (13)

lack of other suitable crystals, this deterioration was considered tolerable.

It seemed probable that in some cases a satellite reflexion might partially or completely overlap with a legitimate reflexion, and the background measurements were checked carefully for signs of partial overlap. The backgrounds were suspiciously uneven for about 30 reflexions, but by decreasing and/or shifting the individual scan ranges it was possible to reduce the unevenness to acceptable levels for about 20 of them. Any cases of complete overlap, of course, were undetected at this stage. The data were corrected for Lorentz and polarization factors, but no attempt to apply absorption corrections was made until later in the analysis.

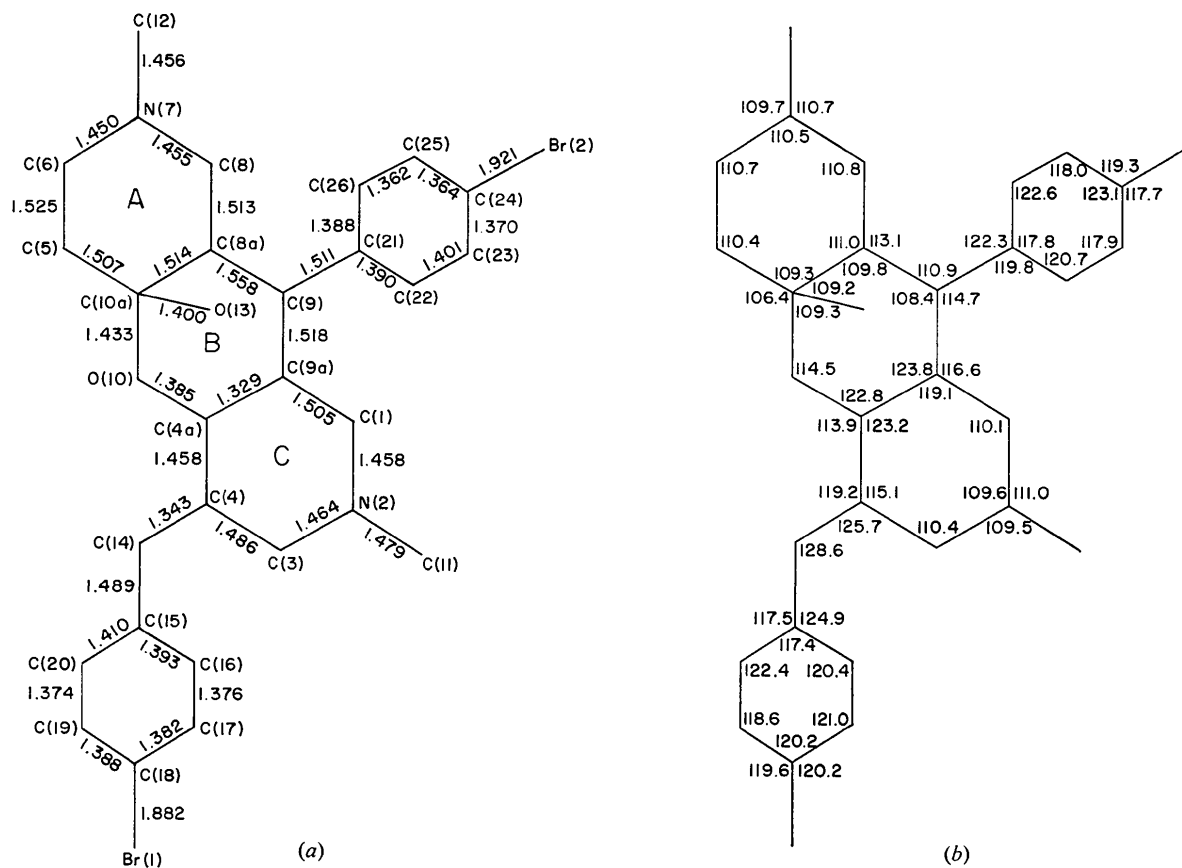
Structure determination and refinement

Location of all the non-hydrogen atoms proceeded routinely by the heavy-atom method. Refinement was by block-diagonal least-squares calculations, minimizing the function $\sum w(|F_o| - |F_c|)^2$. Non-hydrogen atoms were refined first with isotropic temperature factors and later anisotropically. Hydrogen atoms were located on a difference map, and each hydrogen

atom was assigned the average isotropic temperature factor of the atom to which it was bonded, but the hydrogen atom parameters were not refined. Scattering factors for carbon, nitrogen, oxygen and neutral bromine were taken from Hanson, Herman, Lea & Skillman (1964), those for bonded hydrogen from Stewart, Davidson & Simpson (1965), and the real part ($\Delta f' = -0.96$) of the anomalous scattering correction (Cromer, 1965) was applied to the Br curve.

Absorption corrections were calculated at an early stage of the refinement, but the corrected data were eventually abandoned because of unsatisfactory structure factor agreement. The final parameters were obtained by refinement of the uncorrected data. The largest shift in the last least-squares cycle was 0.27σ , and the average (shift/e.s.d.) ratio was 0.06. The final R value $[=\sum(|F_o| - |F_c|)/\sum|F_o|]$ for 3072 observed reflexions without absorption corrections is 0.081. Three reflexions (0,0,18, 125, 126) were excluded from the last few cycles of refinement because of poor structure factor agreement. The weighting scheme was of the form $w = 1/[1 + \{(|F_o| - P_2)/P_1\}^2]$ with $P_1 = P_2 = 30.0$. This reflected reasonably well the trend in $|\Delta F|$'s.

The main differences between the final parameters and the parameters obtained with absorption-corrected



data are in the thermal parameters. The U_{ii} values obtained with the uncorrected data (*cf.* Table 1) are, on average, 0.012 \AA^2 lower than those obtained with the absorption-corrected data. The corresponding e.s.d.'s

are about 0.004 \AA^2 . For 77 of the 99 positional parameters the differences were less than the final respective e.s.d.'s, and for all 99 the differences were less than 2.5σ .

A final difference Fourier synthesis showed several peaks between 0.5 and 1.0 e \AA^{-3} in height near the two Br atoms, and one peak (0.5 e \AA^{-3}) midway between C(8a) and C(9), which is presumably attributable to bonding electron density. No other peaks were higher than 0.4 e \AA^{-3} , which corresponds to 3 times the e.s.d. of the difference density.

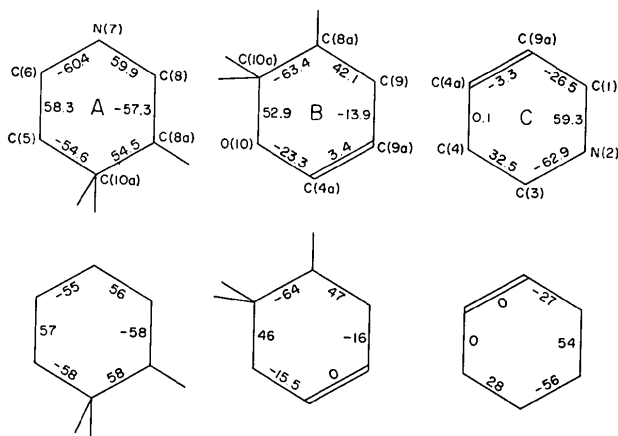


Fig. 2. Observed torsional angles in the three heterocyclic rings and (below) the values calculated for comparable homocyclic systems.

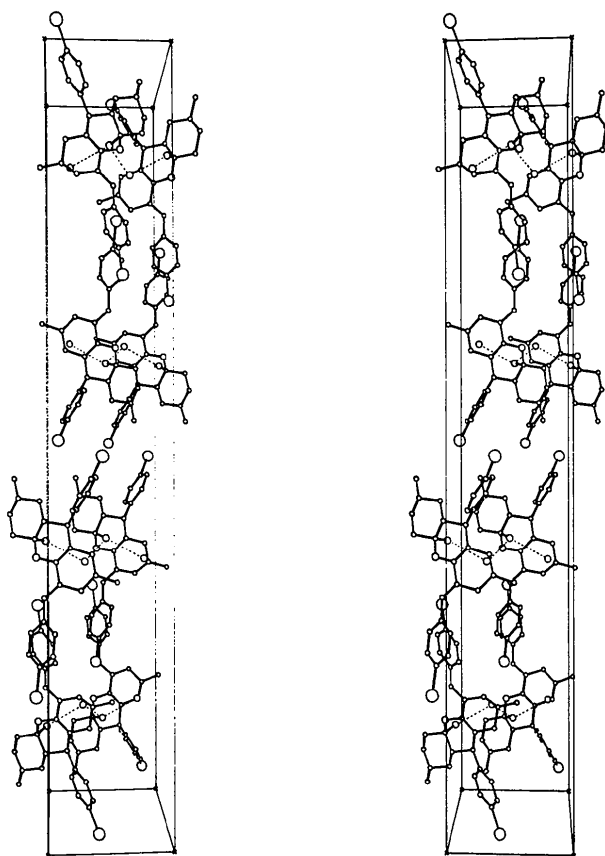


Fig. 3. Stereoscopic view of the packing. The b axis is horizontal and the c axis is vertical. Hydrogen bonds between the water molecules and OH groups are indicated by broken lines.

Results and discussion

Final parameters are given in Tables 1 and 2. The listed e.s.d.'s were obtained from the inverse of the least-squares matrix. The observed and calculated structure factors are compared in Table 3. Unobserved reflexions, which are marked with an asterisk, were assigned the threshold value but were excluded from the least-squares refinement. Fig. 1 shows the numbering scheme for the dimer molecule.

Table 2. *Hydrogen atom positions and assigned B values*

The coordinates were obtained from a difference map and were not refined. They are multiplied by 10^3 . The B value given to each hydrogen atom is that of the atom to which it is bonded.

Bonded to	x	y	z	$B(\text{\AA}^2)$	
H(11)	C(1)	66	437	381	2.8
H(12)	C(1)	165	357	372	2.8
H(31)	C(3)	104	278	311	3.1
H(32)	C(3)	197	270	326	3.1
H(51)	C(5)	-14	-330	396	2.8
H(52)	C(5)	-107	-310	378	2.8
H(61)	C(6)	-145	-409	418	2.7
H(62)	C(6)	-225	-270	419	2.7
H(81)	C(8)	-35	-28	449	2.4
H(82)	C(8)	-145	4	433	2.4
H(8a)	C(8a)	72	-87	410	2.3
H(91)	C(9)	-61	210	408	2.7
H(111)	C(11)	168	540	337	3.6
H(112)	C(11)	81	552	319	3.6
H(113)	C(11)	38	596	349	3.6
H(121)	C(12)	-145	-389	464	4.4
H(122)	C(12)	-87	-242	472	4.4
H(123)	C(12)	-231	-242	462	4.4
H(131)	O(13)	-231	-91	373	2.9
H(141)	C(14)	29	-131	324	3.1
H(161)	C(16)	217	143	289	3.6
H(171)	C(17)	269	119	248	4.4
H(191)	C(19)	0	-206	238	5.1
H(201)	C(20)	-38	-195	284	4.6
H(221)	C(22)	-19	357	444	3.1
H(231)	C(23)	87	445	475	3.6
H(251)	C(25)	367	222	442	3.5
H(261)	C(26)	246	147	411	3.2
H(271)	O(27)	-171	199	364	4.2
H(272)	O(27)	-124	377	352	4.2

Although the final thermal parameters are subject to systematic errors because of the omission of absorption corrections, they were examined for evidence of

'sofa' conformation, with N(2) displaced 0.70 Å from the mean plane through the other 5 atoms. Torsional angles for these three rings are shown in Fig. 2 together with the calculated torsional angles (Bucourt & Hainaut, 1965) for the comparable homocyclic rings. It can be seen that in each ring the observed torsional angles adjacent to the hetero-atom are larger than the calculated values. Comparison with a few other examples of relatively unconstrained piperidine rings (Argos, Barr & Weber, 1970; Brisse, 1970; Karle, 1970; Koch & Germain, 1972) showed the same pattern occurring in the last two examples, but not in the first two.

Both methyl groups are equatorial, and the hydroxyl group is axial. The phenyl group [C(21)–C(26)] is planar within experimental error ($\chi^2=0.80$) and is attached to the dihydropyran ring in a quasi-equatorial orientation. Its conformation relative to the half-chair ring is close to the conformation calculated by Allinger & Tribble (1971) as having the lowest energy in the phenylcyclohexane system (equatorial parallel); *i.e.* the C(9)–H(91) bond is almost parallel to the phenyl plane. The dihedral angle between the phenyl ring plane and the mean plane through C(4a), C(9), C(9a), O(10) is 78.1°, and the torsional angle C(22)–C(21)–C(9)–H(91) is –11.4°. In the structure of 1-*p*-nitrophenyl-3-methylperhydro-2,9-pyridoxazine (Huber, 1972) where a phenyl ring is equatorially bound to a fully saturated (chair-shaped) heterocyclic ring, the conformation of the phenyl group is even closer to 'equatorial parallel'; the torsional angle C(17)–C(12)–C(1)–H(11) is only 4.3°.

In the present structure the other phenyl group [C(15)–C(20)] is also essentially planar ($\chi^2=0.89$). Despite the conjugated double bond system, the ring is twisted by 33.2° about the C(14)–C(15) bond from coplanarity with C(3), C(4), C(4a), C(14). This rotation relieves the H...H repulsion between H(31) and H(161) (non-bonded distance 2.08 Å); without this rotation the nonbonded distance would have been only 1.60 Å, considerably less than the usual van der Waals contact distance (2.4 Å). The H(32)...H(161) and H(141)...H(201) distances are 2.24 and 2.32 Å respectively. It should be noted that the increases in the three angles C(3)–C(4)–C(14) [125.7°], C(4)–C(14)–C(15) [128.6°], C(14)–C(15)–C(16) [124.9°] from their expected value (120°) also serve to increase the H(31)...H(161) distance.

There are no particularly short intra- or intermolecular contacts holding the other aromatic ring in its position. The shortest pertinent H...H distances are H(91)...H(221) [2.33 Å], H(8a)...H(261) [2.81 Å] and H(12)...H(261) [2.87 Å].

Packing and hydrogen bonding

Dimer molecules are hydrogen bonded alternately with water molecules in endless zigzag chains along *b*. The chains are separated from each other by van der Waals contact distances. Fig. 3 shows a stereo view of

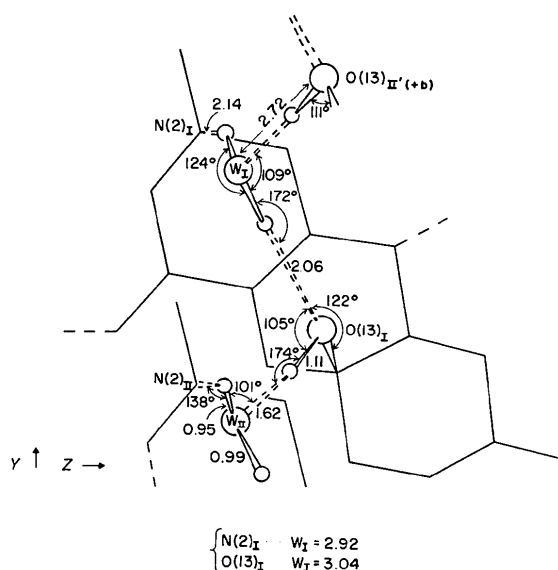


Fig. 4. Hydrogen bonding scheme.

the crystal structure, and Fig. 4 illustrates the hydrogen bonding scheme in more detail. A hydrogen bond extends from the hydroxyl group in dimer molecule I (x, y, z) to water molecule II ($\frac{1}{2} - x, \frac{1}{2} + y, z / -1, -1, 0$) while at the same time water molecule I is more weakly hydrogen bonded to the hydroxyl group and to N(2) in dimer molecule I. The angles at N(2) are quite consistent with the existence of a hydrogen bond from the water molecule; C(1)–N(2)...H is 95°, C(11)–N(2)...H is 107°, and C(3)–N(2)...H is 124°.

The shortest intermolecular distances of the various types (other than those involved in hydrogen bonds) are as follows: Br...Br, 4.18; Br...C, 3.64; Br...N, 3.79; Br...O, 3.31; C...C, 3.47; C...N, 3.44; C...O, 3.34; O...O, 3.91; O...N, 4.71; N...N, > 5.0 Å.

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The Crystal and Molecular Structure of Firefly D(–)-Luciferin

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The structure of firefly luciferin has been confirmed by X-ray diffraction analysis. The compound, $C_{11}H_8O_3N_2S_2$, forms orthorhombic crystals, space group $P2_12_12_1$, with cell dimensions $a=9.410$, $b=22.956$, and $c=5.370$ Å: there are four molecules in the unit cell. The structure was refined by least-squares calculations to an R index of 0.054 for 841 non-zero reflections collected on a diffractometer with $Co K\alpha$ radiation.

Introduction

The blue-green flash of the firefly has been shown to result from the oxidation of the substrate luciferin to yield as a final product dehydroluciferin (Fig. 1).

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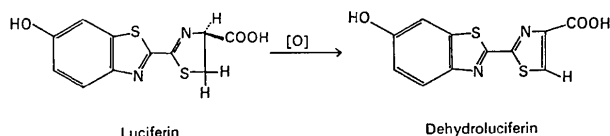
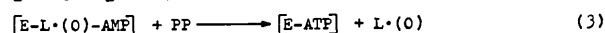
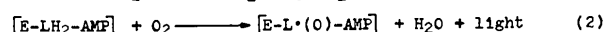
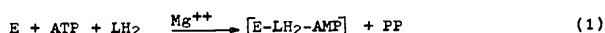


Fig. 1. Oxidation of luciferin.



E = Luciferase
 LH₂ = Luciferin
 PP = Pyrophosphate
 ATP = Adenosine triphosphate
 AMP = Adenosine monophosphate
 L(O) = Oxidized luciferin

Fig. 2. Proposed reactions in the enzymatic oxidation of luciferin.

The enzyme luciferase which catalyzes this reaction in fireflies is stereoselective with respect to the asymmetric center and the luminescent event occurs only when the D(–) isomer is oxidized. The chemical structure of D(–)-luciferin was confirmed by a synthesis involving the condensation of 2-cyano-6-hydroxybenzothiazole and D(–)-cysteine. The condensation product employing the L(+)-cysteine was inoperative in the production of the light burst in the enzyme system (White, McCapra, Field & McElroy, 1961; White, McCapra & Field, 1963).

The series of reactions shown in Fig. 2 have been suggested to explain the observed kinetics of luminescence when D(–)-luciferin, adenosine triphosphate, and luciferase are mixed in the presence of Mg^{2+} and O_2 (McElroy & Seliger, 1963). An interesting feature of the proposed reaction (1), Fig. 2, is the formation of the luciferyl-AMP bond which involves the carboxyl group of luciferin and the primary phosphate group of adenosine monophosphate. Information regarding the absolute configuration of the carboxyl group is essential to studies concerned with the positioning of the substrate on the enzyme surface. It should be noted that dehydroluciferin may be the isolable oxidized form of luciferin but it is thought not to be identical with the product L(O), a bound oxidized form of luciferin associated with an atom of oxygen.

This investigation was undertaken to determine the geometry of the luciferin molecule and, particularly, its absolute configuration.