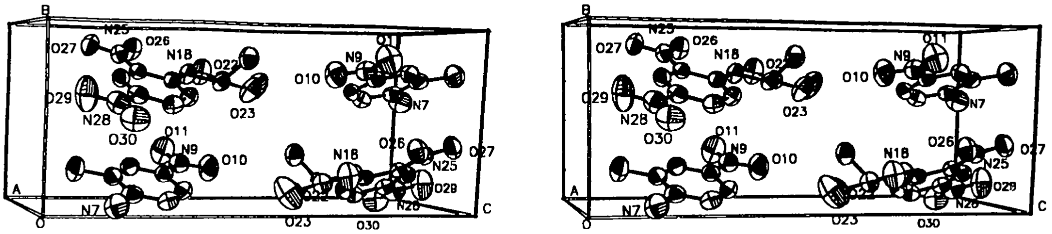

Fig. 1. Stereoscopic *ORTEP*II drawing (Johnson, 1976) of the molecular packing within the unit cell, projected onto the (011) plane. H atoms are omitted.

It is hoped that the crystal will be a good frequency doubler, with good coupling of light in and out of the (001) face. The molecular dipoles are slanted somewhat away from the (001) face normal, so maybe the electric vector of incoming laser radiation will form a significant dot product with the largest expected $\chi^{(2)}_{ijk}$ component (which should be approximately parallel to the resultant of the molecular dipoles). It is significant that the powder second-harmonic generation efficiency (intensity of green light produced at 532 nm from irradiation at 1064 nm from a pulsed Nd:YAG laser) was found in a preliminary experiment to be the same as that of MAP, but less than that of MNA (Rao, Batra, Lal, Evans, Loo, Metzger & Lee, 1991).

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References

Dobosh, P. A. (1967). *Quantum Chem. Program Exch.* **11**, 141.
Hunter, W. E. (1982). *DATRDN*. Univ. of Alabama, USA.
Johnson, C. K. (1976). *ORTEP*II. Report ORNL-5138. Oak Ridge National Laboratory, Tennessee, USA.
Knossow, M., Mauguen, Y. & de Rango, C. (1976). *Cryst. Struct. Commun.* **5**, 719–722.
Levine, B. F., Bethea, L. G., Thurmond, C. D., Lynch, R. T. & Bernstein, J. L. (1979). *J. Appl. Phys.* **50**, 2523–2527.
Lipscomb, G. F., Garito, A. F. & Narang, R. S. (1981). *J. Chem. Phys.* **75**, 1509–1516.
Metzger, R. M. (1976). *J. Chem. Phys.* **64**, 2069–2075.
Metzger, R. M. (1981). Editor. *Cohesive Energy and Ionicity, Springer Topics in Current Physics*, Vol. 26. New York: Springer.
Oudar, J. L. & Hierle, R. (1977). *J. Appl. Phys.* **48**, 2699–2704.
Oudar, J. L. & Zyss, J. (1982). *Phys. Rev. A*, **26**, 2016–2027.
Panunto, T. W., Urbanczyk-Lipkowska, Z., Johnson, R. & Etter, M. C. (1987). *J. Am. Chem. Soc.* **109**, 7786–7797.
Pople, J. A. & Beveridge, D. L. (1969). *Approximate Molecular Orbital Theory*. New York: McGraw-Hill.
Prasad, P. N. & Williams, D. J. (1991). *Introduction to Nonlinear Optical Effects in Molecules and Polymers*. New York: Wiley.
Rao, S. M., Batra, A. K., Lal, R. B., Evans, R. A., Loo, B. H., Metzger, R. M. & Lee, W. J. (1991). *J. Appl. Phys.* **70**, 6674–6678.
Sheldrick, G. M. (1976). *SHELX76*. Program for crystal structure determination. Univ. of Cambridge, England.
Sheldrick, G. M. (1986). *SHELXS86*. Program for the solution of crystal structures. Univ. of Göttingen, Germany.
Whitesell, J. K., Davis, R. E., Saunders, L. L., Wilson, R. J. & Feagins, J. P. (1991). *J. Am. Chem. Soc.* **113**, 3267–3270.

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Structure and Crystal Packing of the Antibacterial Drug 1-{[(5-Nitro-2-furanyl)methylene]amino}-2,4-imidazolidinedione (Nitrofurantoin)

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Abstract. $C_8H_6N_4O_5$, $M_r = 238.16$, monoclinic, $P2_1/n$, $a = 7.845$ (1), $b = 6.462$ (3), $c = 18.920$ (4) Å, $\beta = 93.18$ (2)°, $V = 957.7$ (5) Å^3, $Z = 4$, $D_x = 1.65$ g cm^{-3}, λ(Mo $K\alpha$) = 0.71069 Å, $\mu = 1.318$ cm^{-1}, $F(000) = 488$, $T = 298$ K, $R = 0.040$ for 1052 observed reflections. The configuration around

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the N(3)=C(4) double bond is *E*. The packing arrangement is determined by ribbons of intermolecular N—H···O and C—H···O hydrogen bonds linking the molecules in sheets parallel to (20$\bar{4}$) planes and centrosymmetrically stacked at a distance of approximately 3.2 Å. It is shown that the coupling of the sheets is determined by a dipolar interaction between centrosymmetrically related molecules, whose INDO calculated dipole moment amounts to 8.11 D (= 1.69 e Å = 27.0 × 10^{-30} C m).

Introduction. Since the introduction of nitrofurazone, the first of the chemotherapeutic nitroheterocycles, several other nitrofurans have been synthesized and examined for their antibacterial activity. Out of these only nitrofurantoin is widely employed for human use as a urinary-tract antibacterial drug. However, it presents bio-availability problems which are strictly related to the crystal size and to the two anhydrate and monohydrate crystalline forms (Marshall & York, 1989; Otsuka, Teraoka & Matsuda, 1990). We report here the crystal structure of the anhydrate form and an attempt at rationalization of its crystal packing.

Experimental. A pale-yellow prismatic crystal of dimensions 0.17 × 0.28 × 0.50 mm was used for data collection on an Enraf–Nonius CAD-4 diffractometer with graphite-monochromated Mo $K\alpha$ radiation and $\omega/2\theta$ scans ($2 \le \theta \le 27°$). Cell parameters were determined from 25 reflections in the range $8 \le \theta \le 13°$. 2081 unique reflections were collected ($0 \le h \le 9$, $0 \le k \le 8$, $-23 \le l \le 23$; $R_{\rm int} = 0.030$ on 96 equivalent couples of reflections collected), of which 1052 with $I_o \ge 3\sigma(I_o)$ were used in the refinement. Three standard reflections monitored every 2 h showed no significant variation during data collection. Lorentz and polarization corrections were applied, but absorption was ignored. Solution was by direct methods (*MULTAN*; Main, Fiske, Hull, Lessinger, Germain, Declercq & Woolfson, 1982), refinement by full-matrix least squares on *F*, with anisotropic non-H and isotropic H atoms (all located in a ΔF map). For 178 parameters refined, final $R = 0.040$, $wR = 0.046$ $\{w = 4F_o^2/[\sigma^2(F_o)^2 + (0.05F_o^2)^2]\}$; maximum $\Delta/\sigma = 0.03$, $S = 1.23$; final difference map peaks were in the range -0.20–0.17 e Å^{-3}. Scattering factors were obtained from *International Tables for X-ray Crystallography* (1974, Vol. IV). All calculations were performed with *MolEN* (Fair, 1990) system of programs and *PARST* (Nardelli, 1983).

Table 1. *Atomic positional parameters* (× 10^4, × 10^3 *for* H *atoms) and thermal parameters* (Å^2) *with e.s.d.'s in parentheses*

$B_{\rm eq} = (4/3)\sum_i\sum_j B_{ij}\mathbf{a}_i.\mathbf{a}_j$ for non-H atoms. H atoms were refined isotropically.

	x	*y*	*z*	$B_{\rm eq}/B_{\rm iso}$
O(1)	795 (3)	1366 (3)	4092 (1)	3.89 (5)
O(2)	−2126 (3)	6044 (4)	2700 (1)	4.74 (5)
O(3)	4091 (2)	5535 (3)	5810 (1)	2.50 (4)
O(4)	5697 (3)	2949 (3)	6652 (1)	4.28 (5)
O(5)	6712 (3)	5385 (4)	7334 (1)	4.92 (5)
N(1)	−826 (3)	3331 (4)	3280 (1)	3.00 (5)
N(2)	842 (3)	4940 (3)	4076 (1)	2.65 (5)
N(3)	1933 (3)	5136 (3)	4658 (1)	2.47 (4)
N(4)	5870 (3)	4761 (4)	6810 (1)	3.08 (5)
C(1)	342 (3)	3000 (4)	3853 (1)	2.69 (5)
C(2)	−1145 (4)	5360 (5)	3155 (1)	3.12 (6)
C(3)	−45 (4)	6574 (4)	3683 (2)	3.05 (6)
C(4)	2357 (3)	6977 (4)	4846 (1)	2.71 (6)
C(5)	3510 (4)	7264 (4)	5455 (1)	2.48 (5)
C(6)	5097 (3)	6262 (4)	6355 (1)	2.60 (5)
C(7)	5188 (4)	8331 (4)	6369 (1)	2.86 (5)
C(8)	4161 (4)	8974 (4)	5782 (2)	2.91 (6)
H(1)	−133 (4)	236 (6)	298 (2)	7.3 (9)
H(31)	−75 (4)	734 (5)	401 (1)	4.5 (7)
H(32)	73 (3)	738 (4)	345 (1)	4.2 (7)
H(4)	190 (3)	827 (4)	463 (1)	2.8 (6)
H(7)	587 (3)	904 (4)	670 (1)	3.7 (6)
H(8)	388 (3)	1029 (5)	562 (1)	3.9 (6)

Table 2. *Bond lengths* (Å) *and bond angles* (°) *with e.s.d.'s in parentheses*

O(1)—C(1)	1.195 (3)	N(2)—C(1)	1.373 (3)
O(2)—C(2)	1.206 (3)	N(2)—C(3)	1.447 (4)
O(3)—C(5)	1.369 (3)	N(3)—C(4)	1.280 (3)
O(3)—C(6)	1.348 (3)	N(4)—C(6)	1.411 (3)
O(4)—N(4)	1.214 (3)	C(2)—C(3)	1.504 (4)
O(5)—N(4)	1.228 (3)	C(4)—C(5)	1.437 (3)
N(1)—C(1)	1.397 (3)	C(5)—C(8)	1.353 (4)
N(1)—C(2)	1.353 (4)	C(6)—C(7)	1.339 (4)
N(2)—N(3)	1.363 (3)	C(7)—C(8)	1.397 (4)
C(5)—O(3)—C(6)	104.8 (2)	O(2)—C(2)—C(3)	127.1 (3)
C(1)—N(1)—C(2)	113.0 (2)	N(1)—C(2)—C(3)	107.2 (2)
N(3)—N(2)—C(1)	119.3 (2)	N(2)—C(3)—C(2)	101.7 (2)
N(3)—N(2)—C(3)	127.6 (2)	N(3)—C(4)—C(5)	119.0 (2)
C(1)—N(2)—C(3)	112.8 (2)	O(3)—C(5)—C(4)	117.8 (2)
N(2)—N(3)—C(4)	116.9 (2)	O(3)—C(5)—C(8)	109.6 (2)
O(4)—N(4)—O(5)	124.3 (3)	C(4)—C(5)—C(8)	132.6 (2)
O(4)—N(4)—C(6)	118.3 (2)	O(3)—C(6)—N(4)	116.1 (2)
O(5)—N(4)—C(6)	117.4 (2)	O(3)—C(6)—C(7)	113.0 (2)
O(1)—C(1)—N(1)	126.7 (2)	N(4)—C(6)—C(7)	130.9 (2)
O(1)—C(1)—N(2)	128.1 (2)	C(6)—C(7)—C(8)	104.8 (2)
N(1)—C(1)—N(2)	105.2 (2)	C(5)—C(8)—C(7)	107.8 (2)
O(2)—C(2)—N(1)	125.8 (2)		

Discussion. Final atomic positional and thermal parameters are given in Table 1 and bond distances and angles in Table 2; an *ORTEP*II (Johnson, 1976) view of the molecule is shown in Fig. 1 and the packing of molecules in the unit cell is presented in Fig. 2.*

The molecule, excluding the H atoms, is not far from planar, the maximum displacement from the mean molecular plane being 0.149 (2) and 0.163 (2) Å for the O(2) and O(5) atoms, respectively. The molecular configuration with respect to the C(4)=N(3) double bond is *E*, with a torsion angle N(2)—N(3)—C(4)—C(5) of −179.8 (2)°. The molecular packing can be described as infinite corru-

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* Lists of structure factors and anisotropic thermal parameters have been deposited with the British Library Document Supply Centre as Supplementary Publication No. SUP 55715 (14 pp.). Copies may be obtained through The Technical Editor, International Union of Crystallography, 5 Abbey Square, Chester CH1 2HU, England. [CIF reference: NA1016]

gated sheets parallel (see Fig. 2) to the (20$\bar{4}$) planes (which, accordingly, give the outstanding diffraction intensity). The sheet is stabilized by hydrogen-bonding interactions, described in Table 3 and depicted in Fig. 3. The N(1)—H···O(2) hydrogen bonds connect the molecules related by the *n* glide in infinite ribbons. Owing to the scarcity of hydrogen-bond donors with respect to acceptors, the packing is completed by two C—H···O interactions C(4)—H···O(1) and C(7)—H···O(4), which can be considered weak hydrogen bonds. Both C—H groups involved are close to electronegative atoms which make them presumably more acidic and, consequently, good candidates to be involved in C—H···O hydrogen bonds (Taylor & Kennard, 1982). It seems of some interest that, although these C—H···O interactions are certainly weaker than classical hydrogen bonds, their presence has been reported to be often important in conferring additional stability to molecular associations in biological systems (Jeffrey & Saenger, 1991; Bertolasi, Ferretti, Gilli & Borea, 1990), and in crystal engineering (Sarma & Desiraju, 1986; Desiraju, 1991). The hydrogen-bonded sheets are, in turn, centrosymmetrically stacked in the lattice at an average separation of 3.2 Å, the driving force of such association probably being the coupling of the molecular dipoles. To confirm such a qualitative idea, semi-empirical quantum-chemical INDO (intermediate neglect of differential orbitals) calculations (Phillips, 1975) were accomplished. The total calculated dipole moment assumes the remarkable value of 8.11 D (27.0×10^{-30} C m) and its direction is shown in Fig. 4 for a couple of centrosymmetrically related molecules.

Table 3. *Hydrogen-bond parameters* (Å, °) *with e.s.d.'s in parentheses*

D—H···*A*	*D*···*A*	H···*A*	*D*—H	*D*—H···*A*
N(1)—H(1)···O(2^{i})	2.806 (3)	1.92 (4)	0.92 (4)	162 (3)
C(4)—H(4)···O(1^{ii})	3.374 (3)	2.39 (2)	0.99 (2)	179 (2)
C(7)—H(7)···O(4^{ii})	3.054 (3)	2.53 (3)	0.92 (2)	116 (2)

Symmetry code: (i) $-x-\frac{1}{2}, y-\frac{1}{2}, -z+\frac{1}{2}$; (ii) $x, y+1, z$.

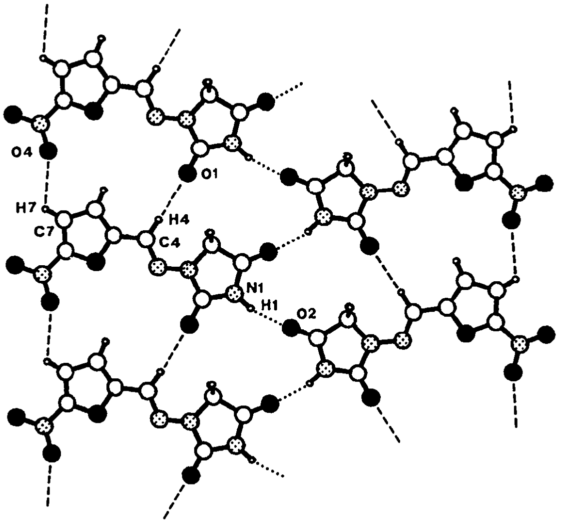

Fig. 3. Packing diagram of molecular layers parallel to (20$\bar{4}$). N—H···O and C—H···O hydrogen bonds are shown as dotted and broken lines, respectively.

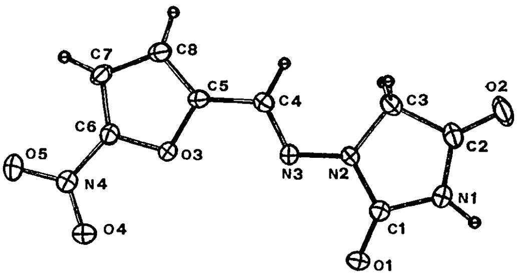

Fig. 1. An *ORTEP*II (Johnson, 1976) view of nitrofurantoin displaying the thermal ellipsoids at 30% probability.

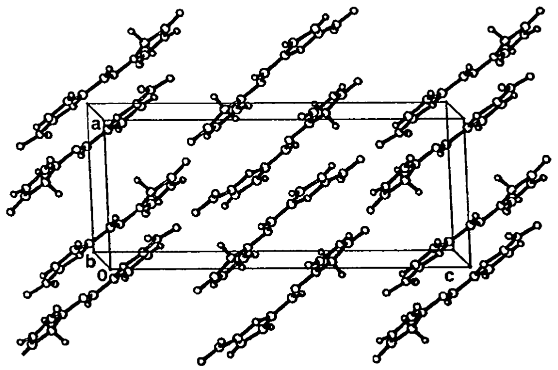

Fig. 2. The unit cell and its contents.

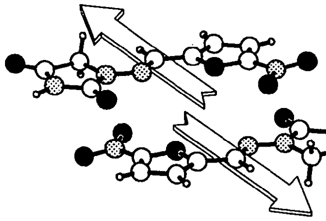

Fig. 4. A couple of centrosymmetrically related molecules. The arrows show the direction of the dipole moments.

Bond distances are regular with the exception of the different bond lengths of the chemically equivalent bonds N(1)—C(1) and N(1)—C(2) of the imidazolidinedione ring which are 1.397 (3) and 1.353 (4) Å, respectively. A survey of the bond distances in similar compounds containing the imidazolidinedione group shows that such bond dissymmetry is usually much smaller with bond-length averages of 1.37 (1) Å (Florencio, Smith-

Verdier & García-Blanco, 1978; Smith-Verdier, Florencio & García-Blanco, 1979; Drew, Mok, Ang & Tan, 1987; Gallucci, Mathur & Shechter, 1992). The dissymmetric situation in the present compound is to be imputed to the fact that only the N(1)—C(2)=O(2) fragment forms infinite chains of hydrogen-bonded amide groups, the mutual relationships between hydrogen-bond strengthening and π-bond delocalization in conjugated systems having been already discussed in detail in previous papers (Gilli, Bellucci, Ferretti & Bertolasi, 1989; Gilli & Bertolasi, 1990).

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References

Bertolasi, V., Ferretti, V., Gilli, G. & Borea, P. A. (1990). *J. Chem. Soc. Perkin Trans.* 2, pp. 283–289.

Desiraju, G. R. (1991). *Acc. Chem. Res.* **24**, 290–296.

Drew, M. G. B., Mok, K. F., Ang, K. P. & Tan, S. F. (1987). *Acta Cryst.* C**43**, 743–745, 745–748, 969–972, 1177–1179.

Fair, C. K. (1990). *MolEN*. An interactive structure solution procedure. Enraf–Nonius, Delft, The Netherlands.

Florencio, F., Smith-Verdier, P. & García-Blanco, S. (1978). *Acta Cryst.* B**34**, 1317–1321.

Gallucci, J., Mathur, N. & Shechter, H. (1992). *Acta Cryst.* C**48**, 477–480.

Gilli, G., Bellucci, F., Ferretti, V. & Bertolasi, V. (1989). *J. Am. Chem. Soc.* **111**, 1023–1028.

Gilli, G. & Bertolasi, V. (1990). *The Chemistry of Enols*, edited by Z. Rappoport, ch. 13, pp. 713–764. New York: John Wiley.

Jeffrey, G. A. & Saenger, W. (1991). *Hydrogen bonding in Biological Structures*. Berlin: Springer-Verlag.

Johnson, C. K. (1976). *ORTEP*II. Report ORNL-5138. Oak Ridge National Laboratory, Tennessee, USA.

Main, P., Fiske, S. J., Hull, S. E., Lessinger, L., Germain, G., Declercq, J.-P. & Woolfson, M. M. (1982). *MULTAN*11/82. *A System of Computer Programs for the Automatic Solution of Crystal Structures from X-ray Diffraction Data*. Univs. of York, England, and Louvain, Belgium.

Marshall, P. V. & York, P. (1989). *Int. J. Pharm.* **55**, 257–263.

Nardelli, M. (1983). *Comput. Chem.* **7**, 95–98.

Otsuka, M., Teraoka, R. & Matsuda, Y. (1990). *Chem. Pharm. Bull.* **38**, 833–835.

Phillips, A. C. (1975). *CNINDO. Quantum Chemistry Program Exchange*, **11**, 274.

Sarma, J. A. R. P. & Desiraju, G. R. (1986). *Acc. Chem. Res.* **19**, 222–228.

Smith-Verdier, P., Florencio, F. & García-Blanco, S. (1979). *Acta Cryst.* B**35**, 216–217.

Taylor, R. & Kennard, O. (1982). *J. Am. Chem. Soc.* **104**, 5063–5070.

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Structure of *N*-Hexadecylpyridinium Chloride Monohydrate

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Abstract. $C_{21}H_{38}N^{+}.Cl^{-}.H_2O$, $M_r = 358.01$, triclinic, $P\bar{1}$, $a = 7.426\,(1)$, $b = 28.301\,(3)$, $c = 5.227\,(1)$ Å, $\alpha = 92.58\,(1)$, $\beta = 99.18\,(1)$, $\gamma = 92.56\,(1)°$, $V = 1081.8\,(3)$ Å^3, $Z = 2$, $D_x = 1.099$ g cm^{-3}, $\lambda(\mathrm{Cu}\ K\alpha) = 1.54178$ Å, $\mu = 16.05$ cm^{-1}, $F(000) = 396$, $T = 158\,(1)$ K, $R = 0.065$, $wR = 0.073$ for 1907 observed reflections. The aliphatic chain is fully extended and inclined to the b axis by 23°. The molecules are packed in a bilayer parallel to the (001) plane. The Cl anion and water of hydration are hydrogen bonded to each other and occupy the interstitial spaces between the hexadecylpyridinium cations. The bond lengths and angles are as expected when the contraction resulting from low-temperature data collection is taken into consideration.

Introduction. The analysis of the title compound was prompted by the very recent understanding that cationic surfactants, in contrast to anionic surfactants, especially of the type of *N*-hexadecylpyridinium chloride (cetylpyridinium-Cl$^-$), exhibit antiviral and antifungal properties at moderate acid pH 6.5 (Paradies & Schröer, 1988; Paradies, 1989, 1991). This work is part of an ongoing study of antiviral biosurfactants with regard to crystal properties and molecular packing of aromatic quaternized N atoms having various alkyl chain lengths, biodegradation properties and different sizes and shapes, when forming micelles in aqueous solutions (Paradies, 1991; Clancy, Tanner, Thies & Paradies, 1992). Counterion dependency of micelle size, structure and shape (Anacker & Ghose, 1968; Anacker, 1958) is also important. In addition, the present

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