

La similitude de la molécule d'HNS et du groupement de deux molécules dans le TNT cristallisé se complète par celle des paramètres de la maille cristalline, outre l'identité des groupes spatiaux. En effet pour le TNT monoclinique nous avons déterminé:  $a = 21,268$  (9),  $b = 6,089$  (1),  $c = 15,020$  (7) Å et  $\beta = 110,10$  (3)° (Gérard & Hardy, 1988).

Par contre spatialement il y a des différences: une caractéristique de la structure du TNT est le parallélisme des molécules selon l'axe  $c$ , ce qui nous a fait décrire cette structure comme une succession de toits d'arête parallèle à  $c$  dont une tuile sur deux serait absente (Sauvestre *et al.*, 1982) (Fig. 3*b*). Bien que selon  $c$  les molécules d'HNS ne soient pas vues de profil, les projections selon cette direction sont parfaitement superposables avec une pente à 45° des tuiles (Fig. 3*a*). Cette ressemblance des deux projections selon  $c$  peut faire supposer que, s'il y a une croissance épitaxiale du TNT sur l'HNS ce serait selon les faces (101).

En conclusion de ces considérations sur l'épitéaxie, il y a une explication de l'amélioration de l'isotropie au cours de la cristallisation du TNT en présence d'HNS (selon  $b$  les cristaux sont moins longs et plus larges). En effet la non épitéaxie dans cette direction limite la longueur des cristaux, alors que l'épitéaxie possible suivant une direction orthogonale à  $b$  tend à développer ces cristaux dans leur épaisseur.

Nous remercions la Direction des Recherches, Etudes et Techniques de la Délégation Générale de l'Armement ainsi que l'Établissement de Fabrication

d'Armement de Bourges pour l'aide financière et les centres de calcul CIRCE du CNRS et CICUP de l'Université de Poitiers pour la réalisation des calculs et graphes nécessaires.

#### Références

- BACK, J. S., SÖDERBERG, J. L. & HAKANSON, C. L. (1970). Brevet français 2 007 049 du 2 janvier 1970 par la société Aktiebolaget BOFORS.
- BOUWSTRA, J. A., SCHOUTEN, A. & KROON, J. (1983). *Acta Cryst.* **C39**, 1121–1123.
- BOUWSTRA, J. A., SCHOUTEN, A. & KROON, J. (1984). *Acta Cryst.* **C40**, 428–431.
- BROWN, C. J. (1966). *Acta Cryst.* **21**, 146–152.
- CARPER, W. R., DAVIS, L. P. & EXTINE, M. W. (1982). *J. Phys. Chem.* **86**, 459–462.
- FINDER, C. J., NEWTON, M. G. & ALLINGER, N. L. (1974). *Acta Cryst.* **B30**, 411–415.
- GÉRARD, F. & HARDY, A. (1988). En préparation.
- GÉRARD, F., HARDY, A., DELACHAUME, J. P. & SAUVESTRE, G. (1985). Rapport DRET-EFAB, NT N° 44/EST/EX.1.
- GRAEBER, E. J. & MOROSIN, B. (1974). *Acta Cryst.* **B30**, 310–317.
- HARDY, A. (1986). Journée Science et Défense de POITIERS, 19 septembre 1986.
- HOLDEN, J. R. & DICKINSON, C. (1977). *J. Phys. Chem.* **81**, 1505–1514.
- International Tables for X-ray Crystallography* (1974). Tome IV, pp. 71, 149. Birmingham: Kynoch Press. (Distributeur actuel Kluwer Academic Publishers, Dordrecht.)
- PARRY, M. A. & THORPE, B. W. (1979). *J. Cryst. Growth*, **46**, 541–550.
- SAUVESTRE, G., DELACHAUME, J. P., GÉRARD, F. & HARDY, A. (1982). Rapport DRET-/EFAB, NT N° 39/EST/EX.1.
- SHELDRIK, G. M. (1976). *SHELX76*. Programme pour la détermination des structures cristallines. Univ. de Cambridge, Angleterre.
- SHIPP, K. G. (1964). *J. Org. Chem.* **29**, 2620–2623.

*Acta Cryst.* (1988). **C44**, 1287–1290

## Structure of (–)-Quinic Acid

BY CHRISTOPHER ABELL, FRANK H. ALLEN,\* TIMOTHY D. H. BUGG, MICHAEL J. DOYLE AND PAUL R. RAITHBY  
*University Chemical Laboratory, Lensfield Road, Cambridge CB2 1EW, England*

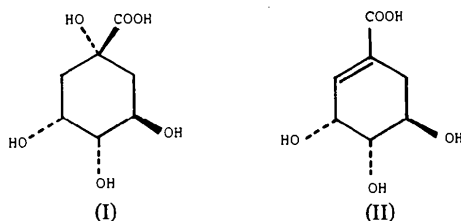
(Received 28 January 1988; accepted 10 March 1988)

**Abstract.** (–)-1 $\alpha$ ,3 $\alpha$ ,4 $\alpha$ ,5 $\beta$ -Tetrahydroxy-1-cyclohexanecarboxylic acid, C<sub>7</sub>H<sub>12</sub>O<sub>6</sub>,  $M_r = 192.2$ , monoclinic,  $P2_1$ ,  $a = 5.667$  (1),  $b = 11.463$  (2),  $c = 6.884$  (2) Å,  $\beta = 113.94$  (2)°,  $V = 408.7$  (2) Å<sup>3</sup>,  $Z = 2$ ,  $D_x = 1.561$  Mg m<sup>-3</sup>, Cu K $\alpha$ ,  $\lambda = 1.54178$  Å,  $\mu = 1.153$  mm<sup>-1</sup>,  $F(000) = 204$ ,  $T = 293$  K,  $R = 0.029$  for 1054 observed reflections [ $I > 3\sigma(I)$ ] and 162 parameters. A positive indication of absolute configuration

[ $\eta = 1.31$  (37)] is in accord with the chemical assignment. The cyclohexane ring adopts a chair conformation with intra-annular torsion angles in the range 49.1 (2)–61.0 (2)° (mean 54.9°). Puckering is enhanced on one side of the ring [C(4)–C(5)–C(6)] and diminished on the other [C(1)–C(2)–C(3)] in order to minimize intramolecular non-bonded O...O interactions. The crystal structure is stabilized by a network of six intermolecular hydrogen bonds with O...O in the range 2.603 (3)–3.022 (3) Å.

\* Author for correspondence.

**Introduction.** (-)-Quinic acid (I) is ubiquitous in plants as the free acid, *e.g.* in cinchona bark and tobacco leaves, or in esterified form, *e.g.* with caffeic acid to yield chlorogenic acid—a major constituent of coffee beans. It can serve as the sole carbon source for many micro-organisms and fungi, where it is converted by the quinate pathway to protocatechuic acid, a key compound in  $\beta$ -keto-adipate synthesis (Weiss & Edwards, 1980). Quinic acid was one of the earliest organic plant products to be isolated (Hofman, 1790), but its structure (Fischer & Dangschat, 1932) and absolute configuration, by conversion to shikimic acid (II) derivatives (Fischer & Dangschat, 1937), were unknown for many years. More recently, Haslam & Turner (1971) confirmed the expected chair conformation in solution by NMR methods. Our interest in (-)-quinic acid stems from its relationship to shikimic acid (II) and to other molecules on the shikimate pathway to the aromatic amino acids in plants and micro-organisms (Conn, 1986). This pathway is of agrochemical interest as a potential target for herbicides. As part of a program designed to obtain accurate structural data for shikimates and related molecules we have recently reported the structure of sodium (-)-shikimate dihydrate (Abell, Allen, Bugg, Doyle & Raithby, 1988). We now report the structure of (-)-quinic acid.



**Experimental.** Colourless prismatic crystals of (-)-quinic acid were obtained by vapour diffusion from water/acetone. Crystal  $0.55 \times 0.40 \times 0.30$  mm; Nicolet R3 $\mu$  diffractometer; graphite-monochromatized Cu  $K\alpha$  radiation; cell parameters refined from diffractometer angles for 25 centred reflections ( $45 < 2\theta < 55^\circ$ ). Intensity data collected by  $\theta$ - $2\theta$  scans for 2233 reflections with  $5 < 2\theta < 116^\circ$  ( $h -6/0$ ,  $k -12/0$ ,  $l -7/7$ ); 3 standard reflections measured in every 100 showed no significant crystal decay; absorption was neglected, 1054 unique reflections ( $R_{\text{int}} = 0.036$ ) with  $I > 3\sigma(I)$  were used in the analysis. Structure solved by multiresolution direct methods, blocked-cascade least-squares refinement on  $F$ , anisotropic thermal parameters for non-H atoms. H atoms located on  $\Delta F$  syntheses, positional parameters refined together with individual isotropic thermal parameters for O—H and two separate overall  $U$ 's for C—H (HO—C—H and H—C—H). 162 parameters,  $R = 0.029$ ,  $wR = 0.039$ ,  $w^{-1} = \sigma^2(F_o) + 0.001F_o^2$ ,  $S = 0.932$ ,  $\Delta/\sigma = 0.016$

(mean) and  $0.077$  (max.),  $\Delta\rho$  variations within  $+0.19$  and  $-0.24 \text{ e \AA}^{-3}$ . Following our experience with sodium (-)-shikimate dihydrate (Abell *et al.*, 1988), we have examined the predictive ability of the Rogers (1981)  $\eta$  parameter for this molecule of known absolute configuration. Despite the fact that only one quadrant of data was collected, the high proportion of oxygen and the use of Cu  $K\alpha$  radiation present favourable conditions. Two refinements were performed using the correct enantiomorph with starting  $\eta$  values of (i)  $-1.0$  and (ii)  $+1.0$ ; final values of  $\eta$  were  $+1.31$  (37) in both cases. No oscillatory movement of  $\eta$  was observed following initial shifts of  $5.7\sigma$  (i) and  $0.83\sigma$  (ii). Simple enantiomorph inversion yielded identical  $R$ ,  $wR$  of  $0.0292$ ,  $0.0391$  in both cases. Here the indication is relatively weak, the ratio (Rogers, 1981)  $(1 + |\eta|)/\sigma(\eta) = 6.2$  being lower than the  $9.8$  observed for the shikimate (Abell *et al.*, 1988). Nevertheless the result is statistically acceptable and consistent with chemical knowledge. The *SHELXTL* program system (Sheldrick, 1983) was used throughout, with scattering factors and  $f'$ ,  $f''$  corrections from *International Tables for X-ray Crystallography* (1974).

**Discussion.** Final atomic parameters are given in Table 1\* and molecular geometry in Table 2. A perspective view of the molecule is shown in Fig. 1, whilst the H-bonding scheme and packing is illustrated in Fig. 2. The crystallographic numbering is based on IUPAC-IUB (1968) recommendations for cyclitols.

The cyclohexane ring conformation in (-)-quinic acid is an almost perfect chair. The mean absolute intra-annular torsion angle of  $54.9^\circ$  may be compared with a value of  $55.9^\circ$  in free cyclohexane in the gas phase (Geise, Buys & Mijlhoff, 1971) or the  $55.5^\circ$  obtained by energy minimization (Bucourt & Hainaut, 1965). There is some distortion, however, in that the torsion angles on one side of the ring [C(4)—C(5)—C(6), see Table 2] exceed the mean value by some  $4-5^\circ$ , whilst there is a compensatory flattening about C(1)—C(2)—C(3). This distortion appears to be a result of the equalization of intramolecular O...O non-bonded interactions around the ring. An examination of Dreiding models shows that increased puckering about C(1)—C(2)—C(3) would shorten the O(1)...O(3) diaxial interaction, whilst reduced puckering about C(4)—C(5)—C(6) would shorten O(4)...O(5) and O(3)...O(4). The observed ring distortions yield near equality of the O...O non-bonded contacts, *viz*: O(1)...O(3) =  $2.866$  (4), O(3)...O(4) =  $2.795$  (4), O(4)...O(5) =  $2.873$  (4) Å.

\* Lists of structure factors, H-atom parameters and anisotropic thermal parameters have been deposited with the British Library Document Supply Centre as Supplementary Publication No. SUP 44847 (10 pp.). Copies may be obtained through The Executive Secretary, International Union of Crystallography, 5 Abbey Square, Chester CH1 2HU, England.

Table 1. Atomic coordinates ( $\times 10^4$ ) and equivalent isotropic temperature factors ( $\text{\AA}^2 \times 10^3$ )

$U_{eq}$  is defined as one-third of the trace of the orthogonalized  $U_{ij}$  tensor.

	<i>x</i>	<i>y</i>	<i>z</i>	$U_{eq}$
C(1)	-2038 (3)	-7640	-2715 (3)	27 (1)
C(2)	-574 (4)	-8100 (1)	-458 (3)	27 (1)
C(3)	-70 (3)	-7195 (1)	1273 (3)	28 (1)
C(4)	-2536 (3)	-6560 (2)	987 (3)	29 (1)
C(5)	-3766 (3)	-6006 (2)	-1198 (3)	28 (1)
C(6)	-4450 (3)	-6950 (2)	-2891 (3)	28 (1)
C(7)	-3003 (4)	-8685 (2)	-4228 (3)	29 (1)
O(1)	-328 (3)	-6926 (1)	-3226 (2)	30 (1)
O(3)	1862 (3)	-6405 (1)	1229 (2)	35 (1)
O(4)	-1864 (3)	-5732 (1)	2701 (2)	38 (1)
O(5)	-5983 (3)	-5327 (1)	-1388 (2)	33 (1)
O(7)	-2357 (3)	-8646 (1)	-5845 (3)	42 (1)
O(8)	-4259 (3)	-9471 (1)	-3927 (2)	37 (1)

Table 2. Molecular geometry for (-)-quinic acid

Distances in  $\text{\AA}$ , angles in  $^\circ$  with e.s.d.'s in parentheses.

C(1)—C(2)	1.528 (3)	C(1)—O(1)	1.417 (2)
C(1)—C(6)	1.541 (3)	C(3)—O(3)	1.431 (2)
C(1)—C(7)	1.535 (2)	C(4)—O(4)	1.440 (2)
C(2)—C(3)	1.517 (3)	C(5)—O(5)	1.438 (2)
C(3)—C(4)	1.516 (3)	C(7)—O(7)	1.306 (3)
C(4)—C(5)	1.517 (3)	C(7)—O(8)	1.216 (3)
C(5)—C(6)	1.521 (3)		
C(2)—C(1)—C(6)	110.8 (2)	C(3)—C(4)—C(5)	111.0 (2)
C(2)—C(1)—C(7)	108.5 (1)	C(3)—C(4)—O(4)	106.6 (1)
C(2)—C(1)—O(1)	107.9 (1)	C(5)—C(4)—O(4)	113.5 (1)
C(6)—C(1)—C(7)	106.7 (1)	C(4)—C(5)—C(6)	109.5 (1)
C(6)—C(1)—O(1)	111.0 (1)	C(4)—C(5)—O(5)	110.5 (2)
C(7)—C(1)—O(1)	111.9 (1)	C(6)—C(5)—O(5)	111.9 (1)
C(1)—C(2)—C(3)	114.4 (1)	C(5)—C(6)—C(1)	111.3 (1)
C(1)—C(2)—C(4)	110.9 (1)	C(1)—C(7)—O(7)	113.9 (2)
C(2)—C(3)—O(3)	108.5 (1)	C(1)—C(7)—O(8)	122.3 (2)
C(4)—C(3)—O(3)	111.5 (1)	O(7)—C(7)—O(8)	123.8 (2)
C(6)—C(1)—C(2)—C(3)	-49.0 (2)	C(3)—C(4)—C(5)—C(6)	61.0 (2)
C(1)—C(2)—C(3)—C(4)	50.8 (2)	C(4)—C(5)—C(6)—C(1)	-59.2 (2)
C(2)—C(3)—C(4)—C(5)	-56.3 (2)	C(5)—C(6)—C(1)—C(2)	52.8 (2)
Hydrogen-bond geometry, H-atom positions normalized to O—H = 0.983 $\text{\AA}$			
O(5)—H(5O)...O(1 <sup>i</sup> )	<i>d</i> (H...O)	<i>d</i> (O...O)	O—H...O
O(5)—H(5O)...O(3)	2.04 (4)	2.915 (3)	147 (2)
O(1)—H(1O)...O(4 <sup>ii</sup> )	2.19 (4)	2.837 (4)	122 (3)
O(7)—H(7O)...O(5 <sup>iii</sup> )	2.03 (4)	2.919 (3)	149 (2)
O(3)—H(3O)...O(8 <sup>iv</sup> )	1.66 (3)	2.603 (3)	159 (3)
O(4)—H(4O)...O(8 <sup>v</sup> )	2.03 (3)	2.857 (4)	141 (3)
	2.19 (4)	3.022 (4)	141 (3)

Symmetry code: (i)  $1 + x, y, z$ ; (ii)  $x, y, z - 1$ ; (iii)  $-1 - x, 0.5 + y, -1 - z$ ; (iv)  $-x, 0.5 + y, -z$ ; (v)  $-1 - x, 0.5 + y, -z$ .

The  $-\text{COOH}$  group is staggered with respect to the ring, with the hydroxy O(7) atom directed towards the  $\alpha$  side of the molecule. Torsion angles about C(1)—C(7) to ring atoms C(2), C(6) are  $-127.3$  (2) and  $113.2$  (2) $^\circ$  for O(7). This brings O(1) and O(7) into an eclipsed arrangement: O(1)—C(1)—C(7)—O(7) =  $-8.3$  (2) $^\circ$ , with a short O(1)...O(7) non-bonded distance of 2.503 (4)  $\text{\AA}$ . This factor, together with the tetrasubstitution at C(1), accounts for the elongation of C(1)—C(7) to 1.536 (3)  $\text{\AA}$ . This value should be

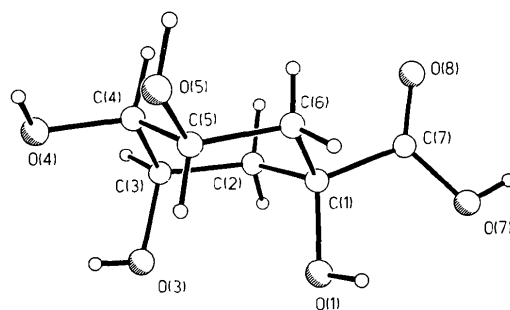


Fig. 1. Perspective view of the structure of (-)-quinic acid (I) showing atomic labelling.

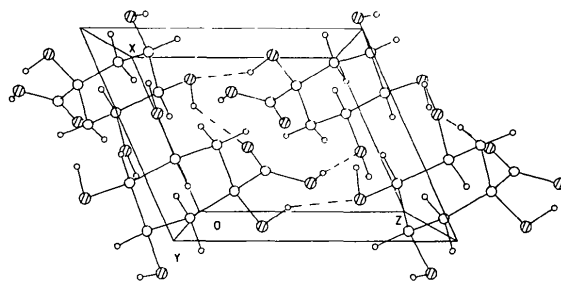


Fig. 2. Packing diagram for (-)-quinic acid (I). H bonds are shown as broken lines.

compared with a standard  $\text{Csp}^3-\text{COOH}$  bond length of 1.502 (1)  $\text{\AA}$  averaged over 176 occurrences in the Cambridge Structural Database (Allen, Kennard, Watson, Brammer, Orpen & Taylor, 1987).

The crystal structure is stabilized by a network of six intermolecular hydrogen bonds (see Fig. 2 and Table 2). All O atoms are involved in the network, and O(5)—H(5O) is involved in a bifurcated interaction with both O(1) and O(3) of the molecule at  $1 + x, y, z$ .

We thank the SERC for provision of equipment and for financial assistance to TDHB. ICI Plant Protection Division and St John's College, Cambridge, are thanked for financial assistance to MJD.

## References

- ABELL, C., ALLEN, F. H., BUGG, T. D. H., DOYLE, M. J. & RAITHBY, P. R. (1988). *Acta Cryst.* **C44**, 1204–1207.
- ALLEN, F. H., KENNARD, O., WATSON, D. G., BRAMMER, L., ORPEN, A. G. & TAYLOR, R. (1987). *J. Chem. Soc. Perkin Trans. 2*, pp. S1–S19.
- BUCOURT, R. & HAINAUT, D. (1965). *Bull. Soc. Chim. Fr.* pp. 1366–1378.
- CONN, E. E. (1986). *Recent Advances in Phytochemistry*, Vol. 20: *The Shikimic Acid Pathway*. New York: Plenum Press.
- FISCHER, H. O. L. & DANGSCHAT, G. (1932). *Chem. Ber.* **65**, 1009–1031.
- FISCHER, H. O. L. & DANGSCHAT, G. (1937). *Helv. Chim. Acta*, **20**, 705–716.
- GEISE, H. J., BUYS, H. R. & MULHOFF, F. C. (1971). *J. Mol. Struct.* **9**, 447–452.

HASLAM, E. & TURNER, M. J. (1971). *J. Chem. Soc.* pp. 1496–1500.  
 HOFMAN, F. C. (1970). *Crell's Ann.* **2**, 314–324.  
*International Tables for X-ray Crystallography* (1974). Vol. IV. Birmingham: Kynoch Press. (Present distributor Kluwer Academic Publishers, Dordrecht.)

IUPAC-IUB (1968). *Eur. J. Biochem.* **5**, 1–8.  
 ROGERS, D. (1981). *Acta Cryst.* **A37**, 734–741.  
 SHELDRICK, G. M. (1983). *SHELXTL Users Manual*, revision 4. Nicolet XRD Corporation, Madison, Wisconsin, USA.  
 WEISS, U. & EDWARDS, J. M. (1980). In *The Biosynthesis of Aromatic Compounds*. New York: John Wiley.

*Acta Cryst.* (1988). **C44**, 1290–1292

## Structure of (-)-3-Dehydroshikimic Acid Monohydrate

BY CHRISTOPHER ABELL, FRANK H. ALLEN,\* TIMOTHY D. H. BUGG, MICHAEL J. DOYLE AND PAUL R. RAITHBY  
*University Chemical Laboratory, Lensfield Road, Cambridge CB2 1EW, England*

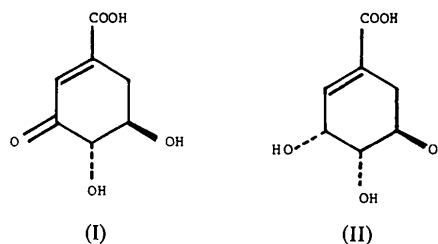
(Received 28 January 1988; accepted 10 March 1988)

**Abstract.** (-)-4 $\alpha$ ,5 $\beta$ -Dihydroxy-3-oxo-1-cyclohexene-carboxylic acid monohydrate, C<sub>7</sub>H<sub>8</sub>O<sub>5</sub>·H<sub>2</sub>O,  $M_r$  = 190.2, monoclinic,  $P2_1$ ,  $a$  = 5.723 (1),  $b$  = 8.554 (1),  $c$  = 8.693 (2) Å,  $\beta$  = 107.14 (1)°,  $V$  = 406.6 (1) Å<sup>3</sup>,  $Z$  = 2,  $D_x$  = 1.553 Mg m<sup>-3</sup>, Cu  $K\alpha$ ,  $\lambda$  = 1.54178 Å,  $\mu$  = 1.157 mm<sup>-1</sup>,  $F(000)$  = 200,  $T$  = 293 K,  $R$  = 0.032 for 1106 observed reflections [ $I > 3\sigma(I)$ ] and 140 parameters. A positive indication of absolute configuration [ $\eta = 1.18$  (40)] is in accord with chemical knowledge. The cyclohexene ring adopts a half-chair conformation, slightly distorted towards the 1,2-diplanar (sofa) form by the 3-oxo substituent. The -COOH group is twisted out of the plane of the endocyclic double bond by 18.7 (3)°. The crystal structure is stabilized by a network of five O—H...O hydrogen bonds with O...O  $\leq$  2.909 (3) Å. The water molecule is involved in three of these interactions, including a very short COO—H...O( $w$ ) bond with O...O = 2.567 (3) Å and O—H...O = 167 (3)°.

**Introduction.** The shikimate pathway is the biosynthetic route to aromatic amino acids in plants and micro-organisms (Weiss & Edwards, 1980; Conn, 1986). The pathway is of agrochemical interest as a potential target for herbicides, hence we have commenced a series of X-ray studies designed to provide accurate structural data, for molecular modelling purposes, of intermediates on the pathway and of related molecules. The structures of sodium (-)-shikimate dihydrate (Abell, Allen, Bugg, Doyle & Raithby, 1988*a*) and (-)-quinic acid (Abell, Allen, Bugg, Doyle & Raithby, 1988*b*) have already been reported. Here we report the structure of (-)-3-dehydroshikimic acid (I) monohydrate. This molecule occupies a key position on the shikimate pathway,

being the immediate precursor of (-)-shikimic acid (II). (I) is the enzyme product of 3-dehydroquinate dehydratase and the substrate for shikimate dehydrogenase. It has been shown to inhibit 3-dehydroquinate dehydratase competitively (Abell & Bugg, 1988).

(-)-3-Dehydroshikimic acid was first isolated by Salamon & Davis (1953) from culture filtrates of a mutant strain of *E. coli*, and has since been isolated from many fungal and plant sources (Weiss & Edwards, 1980). The chemical structure (Salamon & Davis, 1953) was deduced by a variety of analytical and spectroscopic tests, and from its close relationship to shikimic acid whose structure was already known (Fischer & Dangschat, 1934). The conformation of the cyclohexene ring in solution was shown to be a half-chair (Thompson & Haslam, 1974) by <sup>1</sup>H NMR spectroscopy.



**Experimental.** 3-Dehydroshikimic acid was prepared by oxidation of shikimic acid (McKittrick & Ganem, 1985) and purified by high-pressure liquid chromatography, using a Bio-Rad Aminex HPX87H Organic Acids column. Colourless prismatic crystals, shown here to be the monohydrate, were obtained by vapour diffusion from ethyl acetate/light (40–60) petroleum. Crystal 0.32 × 0.45 × 0.53 mm; Nicolet R3*mu* diffractometer; graphite-monochromatized Cu  $K\alpha$  radiation; cell parameters refined from diffractometer

\* Author for correspondence.