

# Structure and hydrogen bonding in 2,4-dihydroxybenzoic acid at 90, 100, 110 and 150 K; a theoretical and single-crystal X-ray diffraction study

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A new polymorph of 2,4-dihydroxybenzoic acid is reported. The structure was characterized by multiple-temperature X-ray diffraction and solid-state DFT computations. The material shows a geometric pattern of hydrogen bonding consistent with cooperativity between the intermolecular carboxylic acid dimer and intramolecular hydrogen bonds. The presence of proton disorder within this hydrogen-bond system, which would support such a cooperative model, was not fully ruled out by the initial X-ray studies. However, solid-state calculations on the three possible end-point tautomers indicate that the dominant crystallographically observed configuration is substantially lower in energy than the other tautomers (by at least 9 kJ mol<sup>-1</sup>), indicating that no disorder should be expected. It is therefore concluded that no disorder is observed either in the intra- or intermolecular hydrogen bonds of the title compound and that the cooperativity between the hydrogen bonds is not present within the temperature range studied.

## 1. Introduction

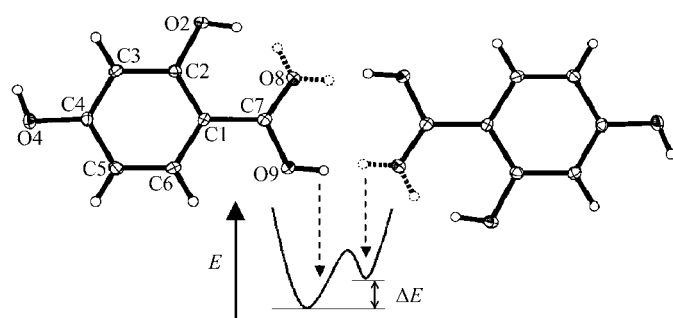
Hydrogen bonds in the 'gas phase' can be regarded as relatively simple interactions, as has been shown by *ab initio* calculations. However, this is not the case in the solid state; there is extensive literature, summarized in Jeffrey (1997), using a wide range of diffraction and spectroscopic methods, indicating that the hydrogen bond in crystalline systems is a highly varied and complex interaction. It is clear that the architecture of hydrogen bonding in the solid state can be controlled by the choice of systems and substituents (forming the basis, for example, of the rapidly growing field of crystal engineering). However, in recent years studies of hydrogen bonding using multi-temperature (multi-T) single-crystal neutron diffraction studies have begun to reveal varied architectures within the same hydrogen bond under a changing external influence (Wilson, 2002). Indeed, the variation of one or more external parameters can be seen in an increasing number of cases to be effectively tuning the 'chemistry' (bond order, electron density) of the hydrogen bond (Parkin *et al.*, 2004). Unusual features in particularly short hydrogen bonds, such as the migration of the H-atom across the hydrogen bond (Wilson *et al.*, 2001; Steiner *et al.*, 2000, 2001) have been studied in some detail, revealing a much more complex chemistry than was previously suspected. Longer hydrogen bonds, such as those observed in substituted benzoic acids, have generally been observed to demonstrate to a greater extent disordered H atoms representative of a classical 'double minimum' model of a hydrogen bond (Fig. 1; Sim *et al.*, 1955; Kanters *et al.*, 1975; Bruno & Randaccio, 1980; Fischer *et al.*, 1985; Destro, 1991; Feld *et al.*, 1981; Wilson *et al.*,

1996*a,b*, 2006; Wilson, 2002). It is worth noting that although these are longer hydrogen bonds, they are generally classed as a medium to strong interaction (Jeffrey, 1997), with typical donor–acceptor distances of 2.55–2.75 Å for materials with O or N atoms as both the donor and acceptor. Related work has shown that both H-atom migration (Parkin *et al.*, 2004) and disorder (Wilson & Goeta, 2004) can also be observed using multi-temperature single-crystal X-ray diffraction; similar observations have also been reported in a comprehensive series of studies by Gilli *et al.* (2004, and references therein).

Over the past 15 years Gilli and co-workers have investigated a number of intramolecular hydrogen-bonding systems – including  $\beta$ -diketones (Gilli *et al.*, 1989; Bertolasi *et al.*, 1996) and 1,3-diketone arylhydrazones (Bertolasi *et al.*, 1993) – where proton transfer involves tautomerism, and therefore a degree of cooperativity between the hydrogen and chemical bonds. These studies have allowed the development of the ideas of charge-assisted and resonance-assisted hydrogen bonding. In combination with our recent work, where we have been systematically studying a range of substituted benzoic acids for possible hydrogen-bond disorder, we became interested in the possibility of cooperativity between intra- and intermolecular hydrogen bonds. As part of this work we have performed a multiple temperature single-crystal X-ray study of a previously unknown polymorph of 2,4-dihydroxybenzoic acid, which is reported here. A single polymorph of this compound was previously reported (Giacomello *et al.*, 1956), with little structural information other than unit-cell parameters made available, but we have not yet been able to grow crystals of this known polymorph. A hydrate form of this material is also known (Horneffer *et al.*, 1999).

## 2. Experimental

X-ray diffraction data were collected from a crystal of 2,4-dihydroxybenzoic acid (purchased from Sigma–Aldrich),



**Figure 1**

The dimerized structure of 2,4-dihydroxybenzoic acid, showing the possible minor fraction disordered components as dashed lines and circles [see (I), (II) and (III)]. One of these hydrogen bonds is mapped onto a schematic diagram illustrating the classical ‘double-minimum’ representation of the energy of a hydrogen bond. This figure can represent either a fully ordered proton or a disordered proton depending on the energy difference between the two forms ( $\Delta E$ ) and the amount of energy in the structure ( $E$ ). In this model,  $E$  is usually strongly correlated with  $T$ , the temperature of the data collection. The dimer is drawn with the thermal ellipsoids from the 90 K data shown at the 30% level; the thermal ellipsoids increase normally with temperature.

**Table 1**

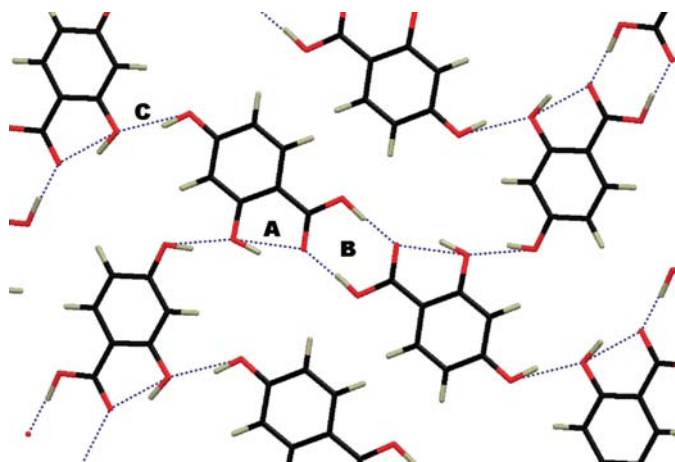
Crystallographic and refinement details for 2,4-dihydroxybenzoic acid at 90 K.

Datasets were also collected at three other temperatures (100, 110 and 150 K); details for these data collections are given in the deposited CIF.

90 K	
<b>Crystal data</b>	
Chemical formula	C <sub>7</sub> H <sub>6</sub> O <sub>4</sub>
$M_r$	154.12
Cell setting, space group	Monoclinic, $P2_1/n$
Temperature (K)	90
$a, b, c$ (Å)	3.6686 (5), 22.333 (3), 8.0046 (11)
$\beta$ (°)	99.630 (3)
$V$ (Å <sup>3</sup> )	646.58 (15)
$Z$	4
$D_x$ (Mg m <sup>-3</sup> )	1.583
Radiation type	Mo $K\alpha$
$\mu$ (mm <sup>-1</sup> )	0.13
Crystal form, colour	Plate, colourless
Crystal size (mm)	0.80 × 0.30 × 0.08
<b>Data collection</b>	
Diffractometer	Nonius Kappa CCD
Data collection method	$\varphi$ and $\omega$ scans
Absorption correction	Multi-scan (based on symmetry-related measurements)
$T_{\min}$	0.96
$T_{\max}$	0.99
No. of measured, independent and observed reflections	5714, 2022, 1301
Criterion for observed reflections	$I > 2.00\sigma(I)$
$R_{\text{int}}$	0.047
$\theta_{\max}$ (°)	33.8
<b>Refinement</b>	
Refinement on	$F^2$
$R[F^2 > 2\sigma(F^2)]$ , $wR(F^2)$ , $S$	0.054, 0.132, 0.96
No. of reflections	2019
No. of parameters	107
H-atom treatment	Mixture of independent and constrained refinement
Weighting scheme	$P = P(6) \cdot \max(F_o^2, 0) + (1 - P(6))F_c^2$ method = <i>SHELXL97</i> (Sheldrick, 1997); $w = 1/[\sigma^2(F^*) + (P(1)p)^2 + P(2)p + P(4) + P(5)\sin(\theta)]$ $P(i)$ are: 0.322E-01 0.690 0.00 0.00 0.00 0.333
$(\Delta/\sigma)_{\max}$	< 0.0001
$\Delta\rho_{\max}, \Delta\rho_{\min}$ (e Å <sup>-3</sup> )	0.71, -0.83
Extinction method	Larson (1970) Crystallographic Computing eq 22
Extinction coefficient	12 (7)

Computer programs used: *COLLECT* (Nonius BV, 1997), *DENZO/SCALEPACK* (Otwinowski & Minor, 1996), *SIR92* (Altomare *et al.*, 1994), *CRYSTALS* (Betteridge *et al.*, 2003), *ORTEP3* (Farrugia, 1997).

recrystallized from acetone solution. The crystal was found to represent a new, monoclinic, polymorphic form, contrasting with the previously reported, triclinic form (Giacomello *et al.*, 1956), for which no structural details are available. To allow the investigation of possible temperature-dependent effects, data sets were collected at 90, 100, 110 and 150 K to allow trends in the behaviour of the hydrogen bonds to be observed. The procedure for using multi-T diffraction to determine relative energies for a double minimum model has been described previously by Wilson *et al.* (1996*a*). The deposited data were collected to  $2\theta = 56^\circ$  on a Bruker–Nonius Kappa CCD diffractometer and the model (obtained by structure

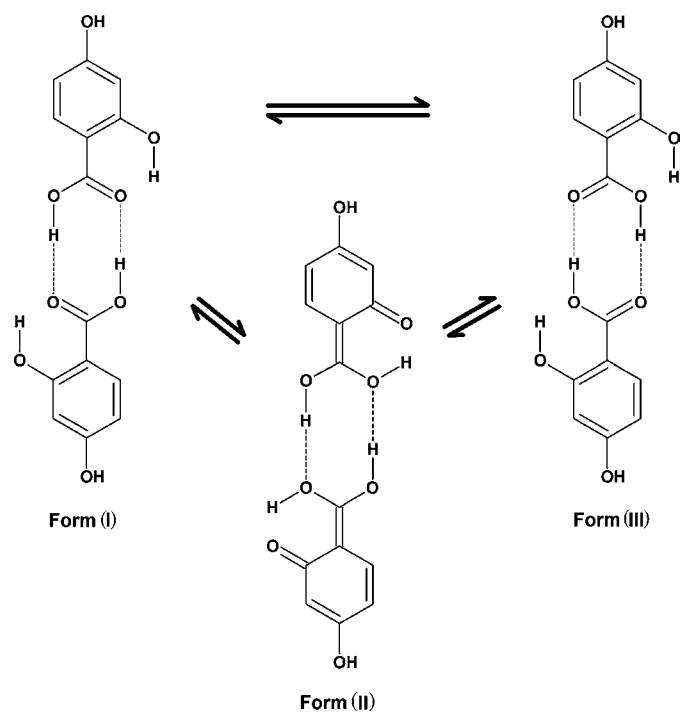


**Figure 2**  
View perpendicular to the puckered hydrogen-bonded sheet in 2,4-dihydroxybenzoic acid, showing the three hydrogen-bonding motifs: (a) intramolecular  $R_1^1(6)$ ; (b) intermolecular  $R_2^2(8)$ ; (c) intermolecular  $O4 \cdots O2$ .

solution in *SIR92*; Altomare *et al.*, 1994) refined against all collected data. The structures were all refined in the program *CRYSTALS* (Betteridge *et al.*, 2003) and difference Fourier sections were computed (without the H atoms involved in the hydrogen bonds) on mean planes through C7, O8 and O9, using only data to  $d$  spacing of 0.8 Å. Maps were produced using the *MAPVIEW* program within *WinGX* (Fig. 2; Farrugia, 1999) and were coloured to represent the difference electron density. Further details on the refinement strategies used can be found in the CIF, which contains details of the most representative refinements carried out at each temperature from one of the crystals examined. Data collection and refinement details at 90 K are summarized in Table 1.<sup>1</sup> Note that the relatively high  $R$  factors observed represent the high quality of the data collected, as the spherical-atom model is no longer completely appropriate for describing molecular structure with these high quality data, while the data are not of sufficient resolution for adopting a multipole refinement model. Data collection was also carried out on a further nine crystals at a variety of temperatures in an attempt to improve our observations; only the highest quality data are included here.

Periodic quantum chemical calculations were carried out on each of the possible tautomeric forms realisable in the structure. These calculations focused on the three end points resulting from proton transfer within the cooperative hydrogen-bonding system (see below), with the intention of obtaining energy differences between these tautomeric forms within the crystal structure. The total energies of lattices composed of dimers in forms (I), (II) and (III) (see below) were obtained from solid-state density functional calculations within the plane-wave pseudopotential formalism, as embodied in the CASTEP code (Segall *et al.*, 2002). The PBE

exchange correlation function (Perdew *et al.*, 1996) was used, along with consistent ultrasoft pseudopotentials. The accuracy of the total energies was ensured by the use of a high basis-set cutoff of 450 eV and a Monkhorst–Pack mesh with a spacing along the reciprocal lattice vectors of less than  $0.05 \text{ \AA}^{-1}$  (Monkhorst & Pack, 1976). Initial structures for the three forms were set manually and the optimization of atomic positions proceeded within fixed cells as obtained from the 90 K X-ray refinement until all atomic forces were less than  $0.01 \text{ eV \AA}^{-1}$ . Current gradient-corrected functionals are known to provide a poor description of weak, long-range interactions, and for this reason we do not attempt to optimize the unit-cell parameters. Recent work has shown that the PBE functional in combination with the plane wave pseudopotential method can provide reliable values for energies of tautomerization in the related compounds benzoic acid, 4-chlorobenzoic acid and terephthalic acid (Middlemiss *et al.*, 2007).



### 3. Results and discussion

The refined molecular structure of the monoclinic polymorph of the title material at 90 K is depicted in Fig. 1, with a view of the crystal packing in Fig. 2. There are, as might be expected from the disposition of the hydrogen-bond donors and acceptors, two dominant hydrogen-bond motifs; an intramolecular  $R_1^1(6)$  and the common  $R_2^2(8)$  intermolecular carboxylic acid dimer motif (Fig. 2). The packing is best described as comprising puckered sheets with approximately planar dimers linked by hydrogen bonds between O4 and O2. Hydrogen-bond geometries are presented in Table 2. Our interest here

<sup>1</sup> Supplementary data for this paper are available from the IUCr electronic archives (Reference: BS5037). Services for accessing these data are described at the back of the journal.

**Table 2**

Hydrogen-bond geometries (including those from the optimized form I calculation).

	$D\cdots A$ (Å)	$D-H$ (Å)	$D-H\cdots A$ (°)
Experimental			
O9–H9 $\cdots$ O8	2.653 (2)	0.9	170.9
O2–H2 $\cdots$ O8	2.632 (2)	0.9	130.3
O4–H4 $\cdots$ O2	2.778 (2)	0.88 (3)	160 (3)
Calculated (form 1)			
O9–H9 $\cdots$ O8	2.594	1.030	174.5
O2–H2 $\cdots$ O8	2.563	1.012	149.2
O4–H4 $\cdots$ O2	2.714	0.999	161.1

focuses on the description of the H atoms in these hydrogen bonds.

Fig. 1 shows the dimeric unit formed by this molecule, held together by the common carboxylic acid dimer (COOH)<sub>2</sub> interaction [ $R_2^2(8)$  graph-set motif], and also the internal intramolecular hydrogen bonds present in the structure. The possible cooperation between these two hydrogen bonds is clear from this figure; the presence of disorder in one of the

**Table 3**

Relative calculated energies of the three possible tautomers evaluated.

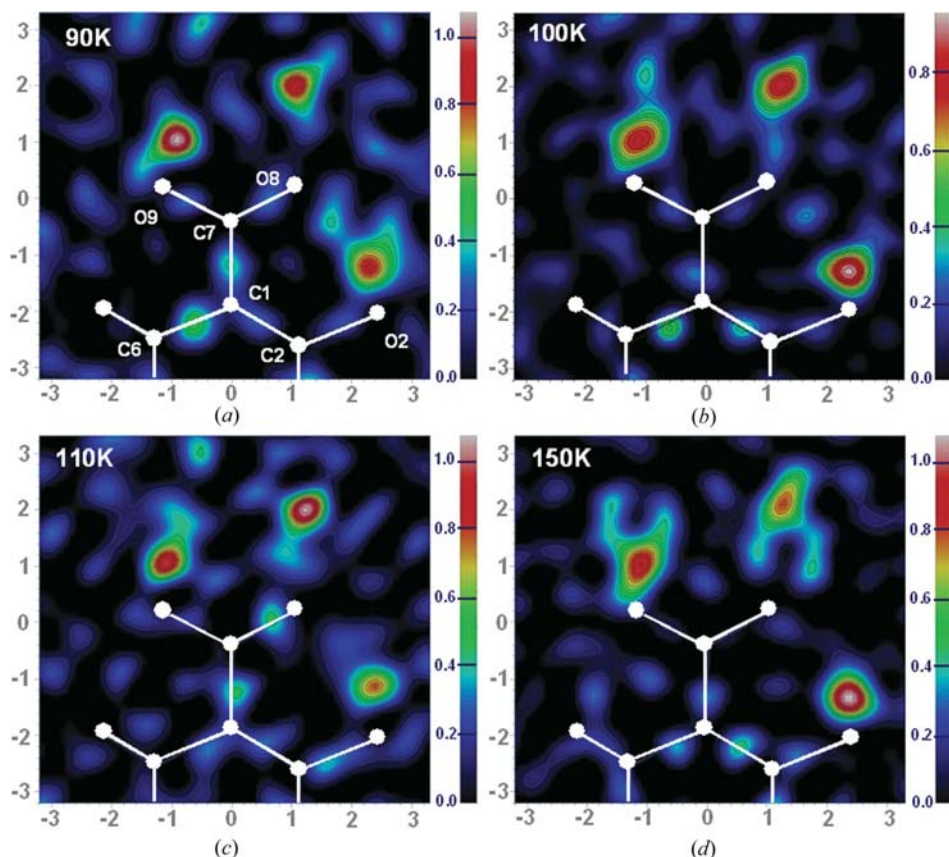
Form	Relative optimized energy (kJ mol <sup>-1</sup> )	Remarks
(I)	0	Low-energy form
(II)	+0.004	Lattice relaxed into form (I), energy comparable to within convergence tolerances
(III)	+8.637	Stable high-energy form

hydrogen bonds may have implications for the disorder of the other, from simple valence arguments. However, the possibility of H-atom disorder in the carboxylic acid is not supported by the C7–O9 and C7=O8 bonds in the different refinements: with C7–O9 having values between 1.318 (2) and 1.322 (2) Å, and C7=O8 between 1.248 (2) and 1.251 (2) Å, there is no discernable change in these bond lengths over the temperature range studied.

Fig. 3 shows the difference-Fourier maps in the plane of the hydrogen bonds for all four temperatures studied. The original

motivation for the computational study of this system arose from the fact that a range of our X-ray difference maps showed small residual density peaks (possibly noise) in regions which might have been indicative of small amounts of disorder. While these remained unconvincing (*cf.* Wilson & Goeta, 2004), after many data collections we concluded that these were not consistent with disorder, the solid-state calculations were undertaken to obtain more understanding of the energetics of these bonds.

The calculations indicate that large energy differences exist between the tautomeric forms of this material. The energies of the optimized configurations for each of the end-point tautomers are presented in Table 3; the energy difference of 8.6 kJ mol<sup>-1</sup> between forms (I) and (III) is large in comparison with typical values obtained for similar systems showing unambiguous proton disorder (Brougham *et al.*, 1997; Horsewill *et al.*, 1998; Wilson *et al.*, 2006; Middlemiss *et al.*, 2007). The large energy difference found in the title compound is most likely a consequence of the inequivalence

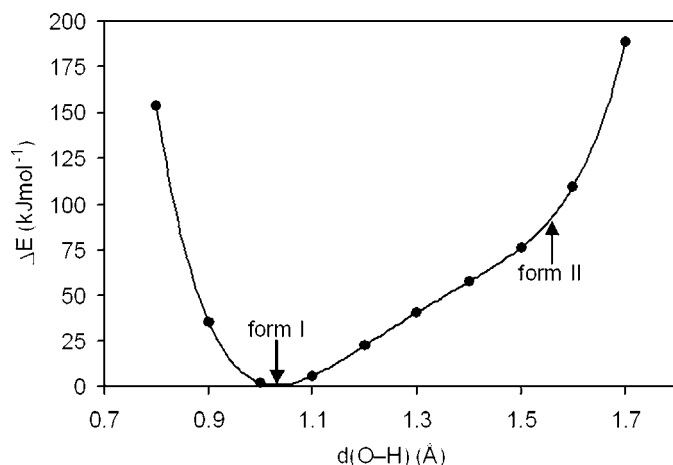

**Figure 3**

Difference-Fourier maps (to a maximum  $\sin \theta/\lambda$  value of 0.625 Å<sup>-1</sup>, 100% completeness) taken from the mean plane through C7, O8 and O9 from datasets collected from the first crystal of the new polymorph of 2,4-dihydroxybenzoic acid at (a) 90, (b) 100, (c) 110 and (d) 150 K (bottom right). All areas of negative electron density are shown shaded dark to make the positive areas clearer; the latter are contoured at 0.06 e Å<sup>-3</sup> intervals. The computations reported here were undertaken in response to the observation of small secondary density peaks at positions consistent with possible cooperative disorder in the hydrogen-bonded system. However, repeated measurements on a range of crystals effectively eliminate this possibility, as do the computations.

of forms (I) and (III) within the dimer, whereas in the other materials studied to date, only interdimer interactions contribute to the asymmetry. The adoption of form (III) would weaken the intramolecular hydrogen bond, since O8 is protonated and therefore cannot accept this intramolecular hydrogen bond as effectively. In addition to this large-energy asymmetry between dimer configurations, the optimized structures show a large difference of 0.09 Å between the (COOH)<sub>2</sub> dimer unit hydrogen-bond lengths in forms (I) and (III). Form (II) is not stable within the optimizations; unconstrained calculations starting from this geometry always resulted in the intramolecular hydrogen-bond proton moving back across the bond into the form (I) structure.

### 3.1. Estimate of form (II) energy

In order to estimate the energy of form (II) a series of calculations were carried out in which the intramolecular hydrogen-bond proton was moved along the line joining the O atoms, starting at a position close to that obtained in form (I). The energy profile of the bond is shown in Fig. 4, from which we obtain an energy for form (II) which is approximately 90 kJ mol<sup>-1</sup> higher than form (I). The energy difference is certainly overestimated, for heavy-atom positions have not been allowed to relax in response to the proton movement, and the orders of the C=O and C–O bonds, in particular, must swap as the proton transfers, without the opportunity to assume optimal length. The contribution of these strained bonds to the energy difference can be estimated within a harmonic model, where the energy required for an excursion of size  $\Delta d$  from the equilibrium bond length is given by  $E = 2\pi\lambda^{-2}c^2\mu(\Delta d)^2$ , where  $\lambda$  is the stretching mode wavelength and  $\mu$  the reduced mass. Taking representative C=O and C–O stretching frequencies of 1750 and 1150 cm<sup>-1</sup>, respectively, and a difference in these bond lengths of 0.086 Å in the optimized form (I) structure, we obtain approximate relaxation energies of 27.5 and 11.8 kJ mol<sup>-1</sup>, respectively. The energy difference between forms (I) and (II) is therefore decreased by this correction to approximately 51 kJ mol<sup>-1</sup>;



**Figure 4**  
Calculated energy profile for linear proton motion across the intramolecular hydrogen bond in form (I).

this value is still sufficiently large to render any significant thermal population of this form improbable below any reasonable estimate of the melting temperature.

## 4. Conclusions

Although disordered protons are of course difficult to locate by X-ray diffraction, there have recently been a range of successful such experiments, from which we and others have previously concluded that with careful data collection it is possible to make reliable qualitative statements regarding the presence of significant amounts of proton disorder in crystal structures. However, in light of the high-energy differences calculated between the possible alternative configurations in the solid state, and with results from high-quality X-ray data showing no convincing evidence for secondary density peaks, we conclude that proton disorder is not present in either the inter- or intramolecular hydrogen bonds in this material. It is proposed to carry out neutron diffraction studies of the title material in order to confirm the validity of the solid-state calculations.

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## References

- Altomare, A., Cascarano, G., Giacovazzo G., Guagliardi, A., Burla, M. C., Polidori, G. & Camalli, M. (1994). *J. Appl. Cryst.* **27**, 435–436.
- Bertolasi, V., Ferretti, V., Gilli, P., Gilli, G., Issa, Y. M. & Sherif, O. E. (1993). *J. Chem. Soc. Perkin Trans. 2*, pp. 2223–2228.
- Bertolasi, V., Gilli, P., Ferretti, V. & Gilli, G. (1996). *Chem. Eur. J.* **2**, 925–934.
- Betteridge, P. W., Carruthers, J. R., Cooper, R. I., Prout, K. & Watkin, D. J. (2003). *J. Appl. Cryst.* **36**, 1487.
- Brougham, D. F., Horsewill, A. J. & Jenkinson, R. I. (1997). *Chem. Phys. Lett.* **272**, 69–74.
- Bruno, G. & Randaccio, L. (1980). *Acta Cryst.* **B36**, 1711–1712.
- Destro, R. (1991). *Chem. Phys. Lett.* **181**, 232–236.
- Farrugia, L. J. (1997). *J. Appl. Cryst.* **30**, 565.
- Farrugia, L. J. (1999). *J. Appl. Cryst.* **32**, 837–838.
- Feld, R., Lehmann, M. S., Muir, K. W. & Speakman, J. C. (1981). *Z. Kristallogr.* **157**, 215–231.
- Fischer, P., Zolliker, P., Meier, B. H., Ernst, R. R., Hewat, A. W., Jorgensen, J. D. & Rotella, F. J. (1985). *J. Solid State Chem.* **61**, 109–125.
- Giacomello, G., Liquori, A. M. & Ripamonti, A. (1956). *Nature*, **177**, 944–945.
- Gilli, G., Bellucci, F., Ferretti, V. & Bertolasi, V. (1989). *J. Am. Chem. Soc.* **111**, 1023–1028.
- Gilli, P., Bertolasi, V., Pretto, L., Ferretti, V. & Gilli, G. (2004). *J. Am. Chem. Soc.* **126**, 3845–3855.
- Horneffer, V., Dreisewerd, K., Ludemann, H.-C., Hillenkamp, F., Lage, M. & Strupat, K. (1999). *Int. J. Mass Spect.* **185**, 859–870.
- Horsewill, A. J., Brougham, D. F., Jenkinson, R. I., McGloin, C. J., Trommsdorff, H.-P. & Johnson, M. R. (1998). *Ber. Bunsenges. Phys. Chem.* **102**, 317–324.
- Jeffrey, G. A. (1997). *An Introduction to Hydrogen Bonding*. New York: Oxford University Press.
- Kanters, J. A., Roelofsen, G. & Kroon, J. (1975). *Nature*, **257**, 625–626.
- Larson, A. C. (1970). *Crystallographic Computing*, edited by F. R. Ahmed, pp. 291–294. Copenhagen: Munksgaard.

- Middlemiss, D. S., Facchini, M. & Wilson, C. C. (2007). Submitted for publication.
- Monkhorst, H. J. & Pack, J. D. (1976). *Phys. Rev. B*, **13**, 5188–5192.
- Otwinowski, Z. & Minor, W. (1996). *Methods Enzymol.* **276**, 307–326.
- Nonius BV (1997). *COLLECT*. Nonius BV, Delft, The Netherlands.
- Parkin, A., Harte, S. M., Goeta, A. E. & Wilson, C. C. (2004). *New J. Chem.* **28**, 718–721.
- Perdew, J. P., Burke, K. & Ernzerhof, M. (1996). *Phys. Rev. Lett.* **77**, 3865–3868.
- Segall, M. D., Lindan, P. L. D., Probert, M. J., Pickard, C. J., Hasnip, P. J., Clark, S. J. & Payne, M. C. (2002). *J. Phys. Condens. Matter*, **14**, 2717–2744.
- Sheldrick, G. M. (1997). *SHELXL97*. University of Göttingen, Germany.
- Sim, G. A., Robertson, J. M. & Goodwin, T. H. (1955). *Acta Cryst.* **8**, 157–164.
- Steiner, T., Majerz, I. & Wilson, C. C. (2001). *Angew. Chem. Int. Ed.* **40**, 2651–2654.
- Steiner, T., Wilson, C. C. & Majerz, I. (2000). *Chem. Commun.* pp. 1231–1232.
- Wilson, C. C. (2002). *Recent Res. Devel. Chem. Phys.* **3**, 119–147.
- Wilson, C. C. & Goeta, A. E. (2004). *Angew. Chem. Int. Ed.* **43**, 2095–2099.
- Wilson, C. C., Shankland, K. & Shankland, N. (2001). *Z. Kristallogr.* **216**, 303–306.
- Wilson, C. C., Shankland, N. & Florence, A. J. (1996a). *Chem. Phys. Lett.* **253**, 103–107.
- Wilson, C. C., Shankland, N. & Florence, A. J. (1996b), *J. Chem. Soc. Faraday Trans.* **92**, 5051–5057.
- Wilson, C. C., Xu, X., Florence, A. J. & Shankland, N. (2006). *New J. Chem.* **30**, 979–981.