

Variable Temperature Neutron Diffraction Analysis of a Very Short O–H···O Hydrogen Bond in 2,3,5,6-Pyrazinetetracarboxylic Acid Dihydrate: Syntho-Assisted Short O_{acid}–H···O_{water} Hydrogen Bond in a Multicenter Array

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Supporting Information

1. Synthesis of pyrazine acids¹⁻³

2,3,5,6-Pyrazine tetracarboxylic acid, 1

A hot solution of KMnO₄ 2.28 g (14.4 mmol) in 10 ml water was added drop wise to the slurry of phenazine (200 mg, 1.1 mmol) in 4 ml hot water containing one pellet of KOH. The mixture was heated on steam bath for 2 h. After adding a few drops of ethanol to destroy excess KMnO₄ the mixture was filtered and the solid MnO₂ cake was washed with two 10 ml portions of water. The filtrate was concentrated to 10 ml on hot plate, cooled and acidified drop wise with conc. HCl. The crude precipitate was washed with hot ethanol and recrystallized from 4 ml of 20% aq. HCl. Yield: 220 mg (77%), M.p. 207 °C, IR (KBr): 3462, 3219, 2363, 1747, 1653, 1454, 1386, 1338, 1277, 1213, 1174, 1134, 831, 748, 709 cm⁻¹.

2,3-Pyrazinedicarboxylic acid, 2

Purchased from Acros Chemicals and used as such for crystallization from water. M.p. 195 °C.

5,6-Dimethylpyrazine-2,3-dicarboxylic acid, 3

Diacid **3** was synthesized by the oxidation of 2,3-dimethyl quinoxaline with KMnO₄, which in turn was obtained by the condensation of diacetyl and *o*-phenylene diamine.

(a) *Preparation of 2,3-dimethylquinoxaline*: 430 mg (4.0 mmol) of *o*-phenylenediamine was dissolved in 7 ml water and the solution was heated to 70 °C. With stirring, a solution of 350 µl (345 mg, 4.0 mmol) of diacetyl in 5 ml hot water (about 80 °C) was

added to the *o*-phenylenediamine solution. The mixture was allowed to stand for 1 h, cooled to room temperature and 1.6 g (19.0 mmol) of Na₂CO₃ was added. Dimethylquinoxaline was extracted with ether and dried over anhydrous MgSO₄. Yield: 200 mg (32%), M.p. 106 °C, ¹H-NMR (CDCl₃): δ 8.0 (dd, 6,3Hz, 2H); 7.7 (dd, 6,3Hz, 2H); 2.7 (s, 6H). IR (KBr): 3447, 2995, 2916, 1489, 1396, 1325, 1165, 987, 761, 611 cm⁻¹.

(b) *Synthesis of 3*: 2,3-Dimethyl quinoxaline 200 mg (1.3 mmol) and 5 ml of water were placed in a flask. With rapid stirring a saturated aqueous solution of 1.17 g (7.4 mmol) of KMnO₄ in 7 ml hot water was added. The reaction mixture was heated at 70 °C for 1 h. After decolorization of KMnO₄, the solution was filtered to discard the MnO₂ cake. The filtrate was gently stirred while adding 1 ml of conc. HCl. Water was removed under reduced pressure until the moist cake of solid KCl and compound **3** remained in the flask. To the solid material 1 ml water and 10 ml acetone were added and then the mixture was boiled at reflux for 15 min. then cooled to room temperature and filtered. Evaporation of the acetone filtrate yielded compound **3**. Diacid **3** was recrystallized from ethanol/benzene (1:1). Yield: 106 mg (64%). M.p. 205 °C. ¹H-NMR (DMSO-d₆): δ 2.6 (s, 6H). IR (KBr): 2910, 1736, 1581, 1439, 1388, 1259, 1194, 1049, 788, 731 cm⁻¹.

Pyrazine-2,3,5-tricarboxylic acid, 5, from 2-(D-Arabo)-tetraoxybutyl quinoxaline:

(a) *2-(D-Arabo)-tetraoxybutyl quinoxaline*: 1.0 g (5.5 mmol) of D-glucose, 800 mg (7.3 mmol) of *p*-toluidine, 250 µl of water and 60 µl of 2 N acetic acid were taken in a conical flask and the mixture was heated in a water bath for 30 min. The syrup formed during the reaction was allowed to cool for 2 h. Later, 500 µl (500 mg, 10.0 mmol) of hydrazine hydrate, 1.16 g (10.7 mmol) of *o*-phenylenediamine, and 8.3 ml of 2N acetic acid were added to the cooled syrup and again the mixture was heated for 20-30 min. The solution was left undisturbed overnight. The product formed was washed with alcohol-ether mixture and dried. Yield: 500 mg (50%). M.p. 185-187 °C. ¹H-NMR (DMSO-d₆): δ 9.0 (s, 1H); 8.0-8.2 (m, 2H), 7.7-7.9 (m, 2H), 5.6 (d, 6Hz, 1H), 5.1 (d, 6Hz, 2H), 4.6 (dd, 17,6Hz, 2H), 4.4 (dd, 6,6Hz, 1H), 3.6-3.8 (m, 5H). IR (KBr): 3337, 3242, 1471, 1338, 1107, 1043, 979, 875, 758, 636 cm⁻¹.

(b) *Pyrazine-2,3,5-tricarboxylic acid*, **5**: 500 mg (2.0 mmol) of 2-(D-Arabo)-tetraoxybutyl quinoxaline was dissolved in 10 ml hot water in a round bottom flask, which was immersed in an oil bath maintained at 90-98 °C. To the yellow solution, which was stirred mechanically, KOH (250 mg, 4.5 mmol) was added. The color changed from yellow to red. Potassium permanganate (3.7 g, 23.0 mmol), dissolved in a minimum amount of hot water, was added drop wise to the reaction mixture over about 45-60 min. The reaction was allowed to proceed for 3 h. After adding a few drops of ethanol to destroy the excess KMnO₄ the mixture was filtered and the solid MnO₂ cake was washed with two 3 ml portions of water. The filtrate was evaporated in vacuum to 2 ml, cooled, and acidified drop wise with conc. HCl. The crude white precipitate of **5**, formed after 15-20 min. was filtered, dried and recrystallized from 20% HCl. Yield: 200 mg (40%). M.p. 184 °C. ¹H-NMR (DMSO-d₆): δ 9.2 (s, 1H). IR (KBr): 3196, 2505, 1738, 1452, 1402, 1307, 1174, 1101, 935, 823, 792, 594 cm⁻¹.

2. Neutron diffraction of 2,3,5,6-pyrazinetetracarboxylic acid dihydrate 1

A plate-like pale yellow single crystal of 2,3,5,6-pyrazine tetracarboxylic acid dihydrate of dimensions 0.6 × 1.6 × 2.8 mm, calculated volume 3.65 mm³, was mounted on a 1 mm diameter vanadium pin using two-component Kwikfill glue and sealed in a Displex cryorefrigerator⁴ on D9 instrument at the Institut Laue Langevin. D9 is equipped with an 8 degree × 8 degree multiwire (32 × 32) position-sensitive detector and is optimized for accurate neutron intensity measurements at short wavelength. At the chosen wavelength ($\lambda = 0.8397(1)$ Å) from a Cu (220) monochromator in transmission, the crystal was cooled carefully at the rate of 2 degrees per minute to 20 K, while monitoring a strong low-angle reflection. No change in mosaic was observed. Unique reflections to a 2 θ value of 64° were measured, in several shells of increasing resolution; using ω step scans with step times of 2 to 6 sec. The crystal was then warmed slowly to 100 K, to 200 K and to 293 K and the structure redetermined at each temperature, just as at 20 K. Finally, the crystal was re-cooled to 100 K and additional higher-resolution data to 2 θ values beyond 72° were measured to provide a very accurate data set suitable for possible X-N analysis. Standard reflections were monitored periodically, and showed no significant variation.

The space group was at all temperatures consistent with that found in the earlier X-ray work. Bragg intensities were integrated using the ILL program Racer, which employs the method of Wilkinson et al.⁵ Precise unit cell dimensions were calculated at all temperatures using the ILL program Rafd9. The integrated intensities were corrected for attenuation by the crystal (calculated $\mu = 1.10 \text{ cm}^{-1}$, typical minimum and maximum transmission coefficients being *e.g.* 0.8515 and 0.9407 at 100 K) with the program Datap, using a Gaussian integration method.⁶ As a further check on the attenuation correction, F^2 was measured as a function of ψ , the angle of rotation about the scattering vector, for several strong reflections. The final corrected data are of outstanding quality, typical of D9 measurements at short wavelength, where absorption and extinction effects are minimized. Crystal data and details of data collections, structure solutions and refinements are summarized in Tables S1.

3. X-ray diffraction of pyrazine acids **2** and **5**

The X-ray diffraction intensities for acid **2** and **5** were collected at 123(2) and 120(2) K, respectively, (Oxford Cryosystems cryostat) on a Bruker SMART CCD diffractometer (Bruker Systems Inc.)⁷ using Mo- $K\alpha$ X-radiation ($\lambda = 0.71073 \text{ \AA}$). Data were processed using the Bruker *SAINTE* package⁷ with structure solution and refinement run on *SHELX97*.⁸ The structures of both compounds were solved by direct methods and refined by full-matrix least squares on F^2 . H-atoms were located in the difference electron density maps and refined freely with isotropic displacement parameters. Crystallographic data are summarized in Table S2.

4. Crystallographic data

Table S1. Crystallographic data and structure refinement parameters of pyrazine tetracarboxylic acid **1** (neutron diffraction) at different temperatures.

	1 (123 K)^a	1 (293 K)	1 (200 K)	1 (100 K)	1 (20 K)
emp. form.	C ₈ H ₄ N ₂ O ₈ · (H ₂ O) ₂	C ₈ H ₄ N ₂ O ₈ · (H ₂ O) ₂	C ₈ H ₄ N ₂ O ₈ · (H ₂ O) ₂	C ₈ H ₄ N ₂ O ₈ · (H ₂ O) ₂	C ₈ H ₄ N ₂ O ₈ · (H ₂ O) ₂
form. wt.	292.16	292.16	292.16	292.16	292.16
crystal system	Triclinic	Triclinic	Triclinic	Triclinic	Triclinic
space group	$P\bar{1}$	$P\bar{1}$	$P\bar{1}$	$P\bar{1}$	$P\bar{1}$

<i>a</i> [Å]	5.4409(3)	5.4950(10)	5.4606(10)	5.4385(10)	5.4361(10)
<i>b</i> [Å]	6.4041(3)	6.4410(10)	6.4133(10)	6.3885(10)	6.3699(10)
<i>c</i> [Å]	8.6995(3)	8.7670(10)	8.7164(10)	8.6809(10)	8.6672(10)
α [deg]	98.572(3)	99.393(6)	98.962(5)	98.381(5)	97.911(5)
β [deg]	107.374(3)	107.565(7)	107.408(5)	107.406(5)	107.546(5)
γ [deg]	105.519(3)	105.174(7)	105.348(5)	105.573(5)	105.718(5)
<i>Z</i>	1	1	1	1	1
Volume [Å ³]	269.97(2)	275.44(8)	271.57(7)	268.72(7)	267.48(7)
<i>D</i> _{calc} [g/cm ³]	1.797	1.761	1.785	1.804	1.813
<i>T</i> [K]	123(2)	293(1)	200(1)	100(1)	20(1)
<i>F</i> (000)	150	100	100	100	100
2 θ range	6.82–54.88	6.0–64.2	5.98–64.22	6.0–80.28	6.0–64.18
Index ranges	–7 ≤ <i>h</i> ≤ 7	–1 ≤ <i>h</i> ≤ 6	–1 ≤ <i>h</i> ≤ 6	–1 ≤ <i>h</i> ≤ 8	–1 ≤ <i>h</i> ≤ 6
	–8 ≤ <i>k</i> ≤ 8	–8 ≤ <i>k</i> ≤ 7	–8 ≤ <i>k</i> ≤ 7	–9 ≤ <i>k</i> ≤ 9	–8 ≤ <i>k</i> ≤ 7
	–11 ≤ <i>l</i> ≤ 11	–10 ≤ <i>l</i> ≤ 10	–10 ≤ <i>l</i> ≤ 10	–13 ≤ <i>l</i> ≤ 12	–10 ≤ <i>l</i> ≤ 10
N-total	2300	1295	1297	3123	1333
N-independent	1219	1122	1123	1915	1123
N-observed	1125	1040	1034	1762	1088
Parameters	107	135	135	135	135
<i>R</i> ₁	0.030	0.021	0.020	0.023	0.019
<i>wR</i> ₂	0.082	0.046	0.048	0.046	0.043
GOF	1.082	1.120	1.128	1.168	1.222

^a X-ray data are given for comparison.

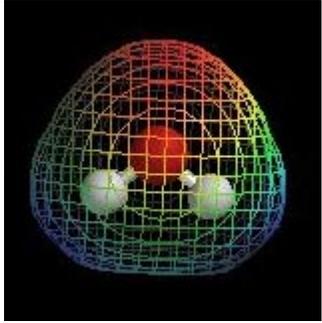
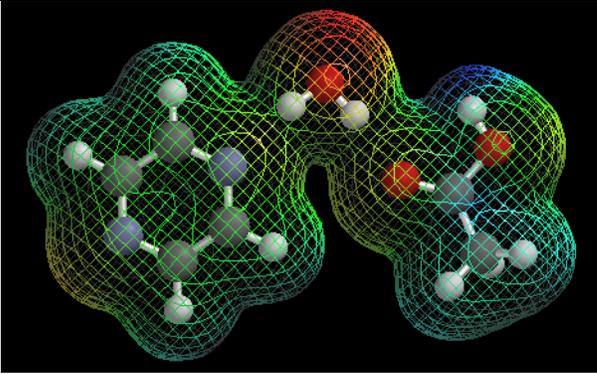
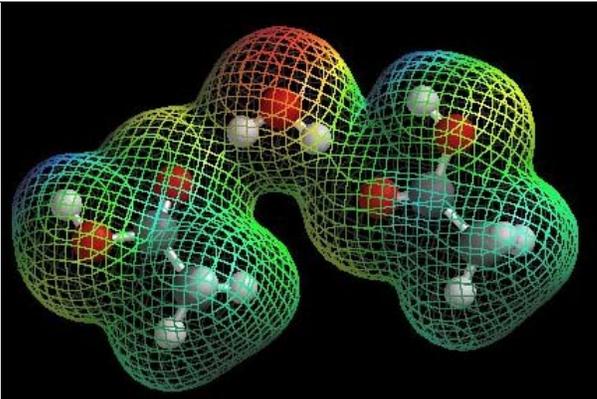
Table S2. X-ray crystallographic data and structure refinement parameters of acids **2-5**.

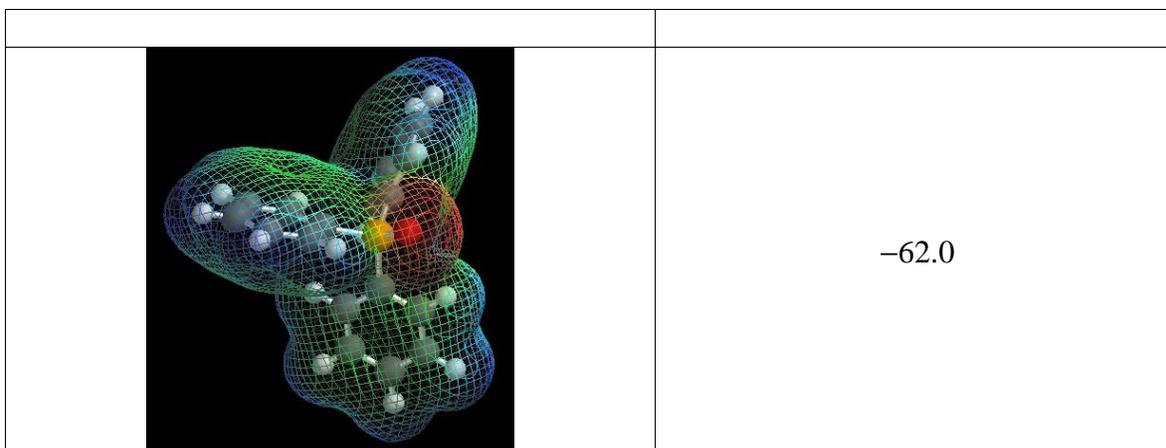
	2	3	4	5
emp. form.	C ₆ H ₄ N ₂ O ₄ · (H ₂ O) ₂	C ₈ H ₈ N ₂ O ₄ · (H ₂ O) ₂	C ₆ H ₄ N ₂ O ₄ · (H ₂ O) ₂	C ₇ H ₄ N ₂ O ₆ · (H ₂ O) ₂
form. Wt.	204.14	232.19	204.14	248.15
crystal system	Monoclinic	Orthorhombic	Triclinic	Triclinic
Space group	<i>C2/c</i>	<i>Pbcn</i>	<i>P</i> $\bar{1}$	<i>P</i> $\bar{1}$
<i>a</i> [Å]	5.3470(2)	12.6454(3)	5.2101(2)	5.2830(3)
<i>b</i> [Å]	13.0286(4)	9.0812(3)	6.8261(2)	6.6497(3)
<i>c</i> [Å]	11.7443(4)	8.8800(3)	6.8713(2)	13.8423(7)
α [deg]	90	90	119.144(2)	93.064(2)
β [deg]	99.036(1)	90	99.808(2)	90.513(2)
γ [deg]	90	90	99.927(2)	103.009(2)
<i>Z</i>	4	4	1	2
Volume [Å ³]	808.00(5)	1019.74(5)	200.85(1)	473.02(4)
<i>D</i> _{calc} [g/cm ³]	1.678	1.512	1.688	1.742
<i>T</i> [K]	123(2)	123(2)	153(2)	120(2)
<i>F</i> (000)	424	488	106	256
2 θ range	6.26–54.98	7.18–54.96	6.9–54.86	2.94–54.98
Index ranges	–6 ≤ <i>h</i> ≤ 6	–16 ≤ <i>h</i> ≤ 16	–6 ≤ <i>h</i> ≤ 5	–6 ≤ <i>h</i> ≤ 6
	–16 ≤ <i>k</i> ≤ 16	–11 ≤ <i>k</i> ≤ 11	–8 ≤ <i>k</i> ≤ 7	–8 ≤ <i>k</i> ≤ 8
	–15 ≤ <i>l</i> ≤ 15	–11 ≤ <i>l</i> ≤ 11	–8 ≤ <i>l</i> ≤ 8	–17 ≤ <i>l</i> ≤ 17

N-total	5412	2132	1268	7415
N-independent	927	1161	875	2172
N-observed	853	1059	781	1887
Parameters	80	97	80	186
R_1	0.029	0.031	0.032	0.033
wR_2	0.083	0.086	0.091	0.093
GOF	1.049	1.069	1.052	1.043

4. Electrostatic potential surface maps

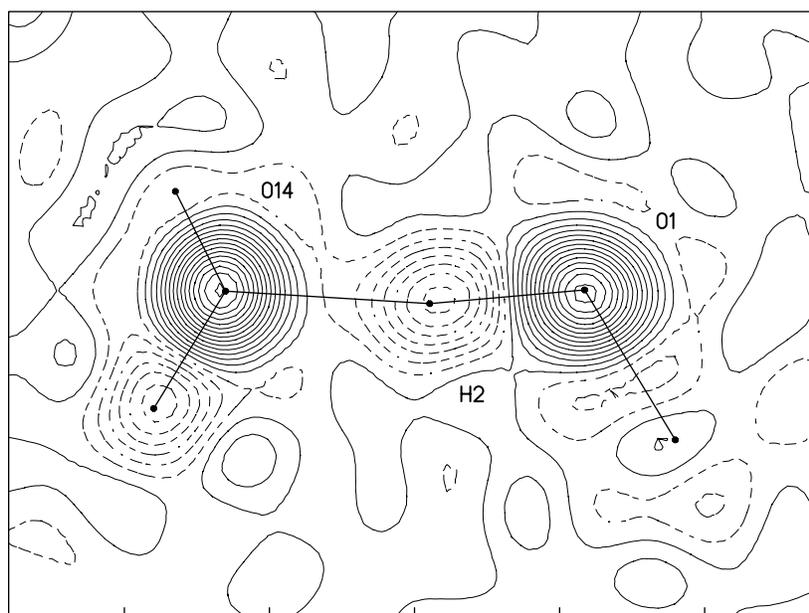
Fig. S1. Spartan (RHF/6-31G*) single point energy calculation on H₂O, CH₃COOH·H₂O·pyrazine, CH₃COOH·H₂O·CH₃COOH and Ph₃P=O. Note the increase in ESP of water oxygen upon hydrogen bonding to a value equal to that of P=O oxygen.

Electrostatic potential surface	ESP on water oxygen (kcal mol ⁻¹)
	-46.2
	-64.4
	-65.2

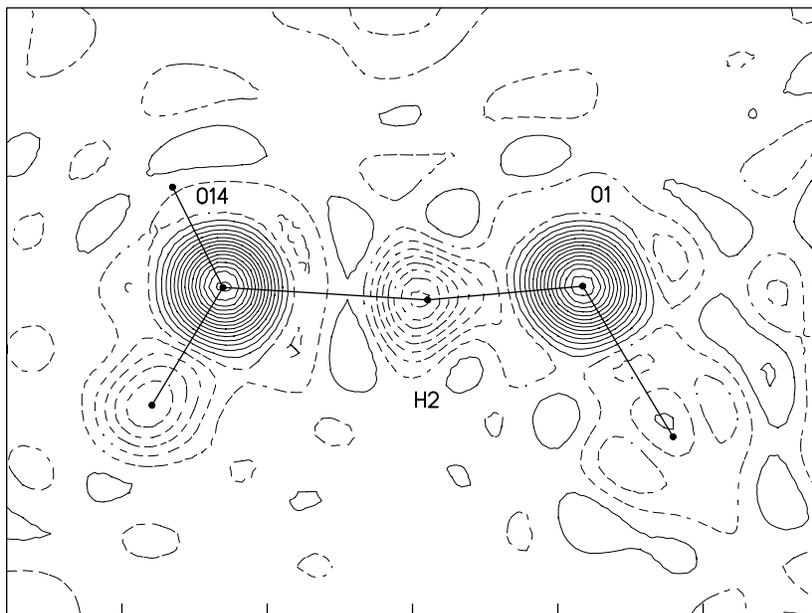


5. Fourier maps of pyrazine tetra acid 1 from neutron diffraction data

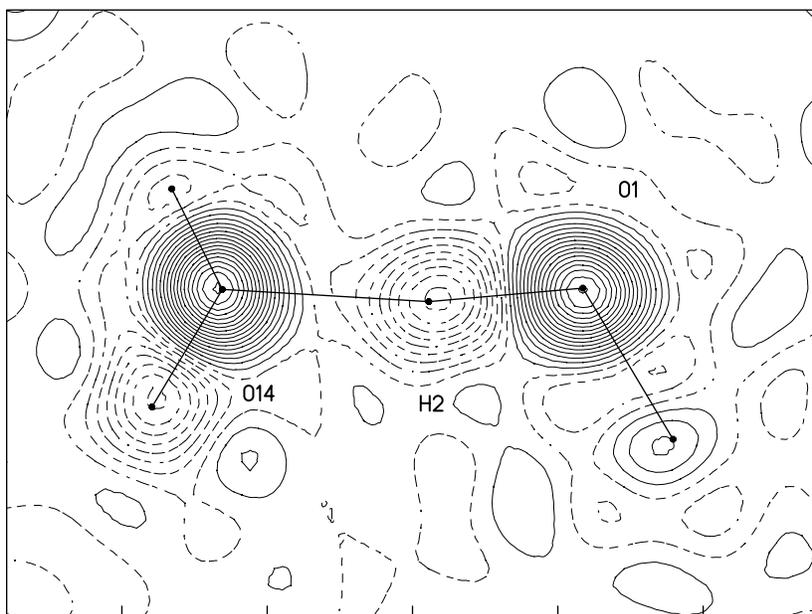
Fig. S2. Contour plots from neutron diffraction data of pyrazine tetracarboxylic acid **1** at different temperatures.



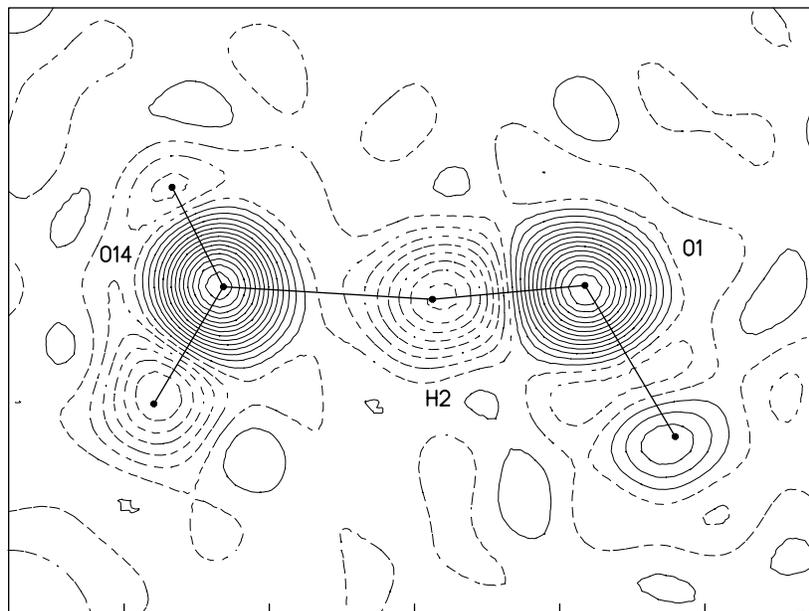
(a) 20 K. The projection is perpendicular to the plane of O1, O14 and H2. Contours are shown in intervals of 3 units from -21 (minimum -21.71) to +42 (maximum +42.70).



(b) 100 K. The projection is perpendicular to the plane of O1, O14 and H2. Contours are shown in intervals of 4 units from -30 (minimum -30.38) to $+58$ (maximum $+58.64$).



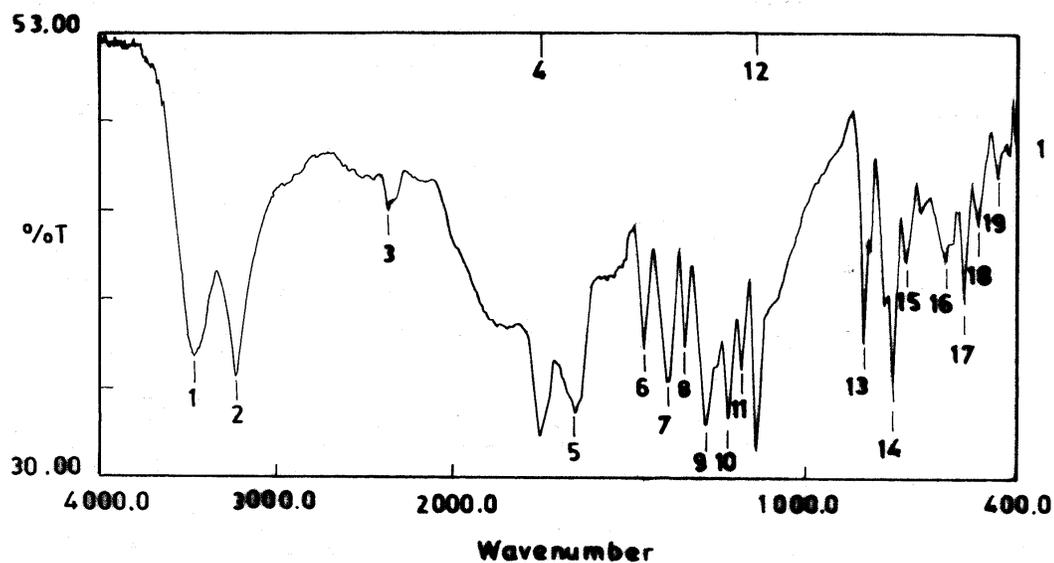
(c) 200 K. The projection is perpendicular to the plane of O1, O14 and H2. Contours are shown in intervals of 2 units from -17 (minimum -17.38) to $+33$ (maximum $+33.45$).



(d) 293 K. The projection is perpendicular to the plane of O1, O14 and H2. Contours are shown in intervals of 2 units from -15 (minimum -15.55) to $+27$ (maximum $+28.58$)

6. Infrared spectra

Fig. S3. IR spectra of tetra acid **1** recorded in KBr and nujol.



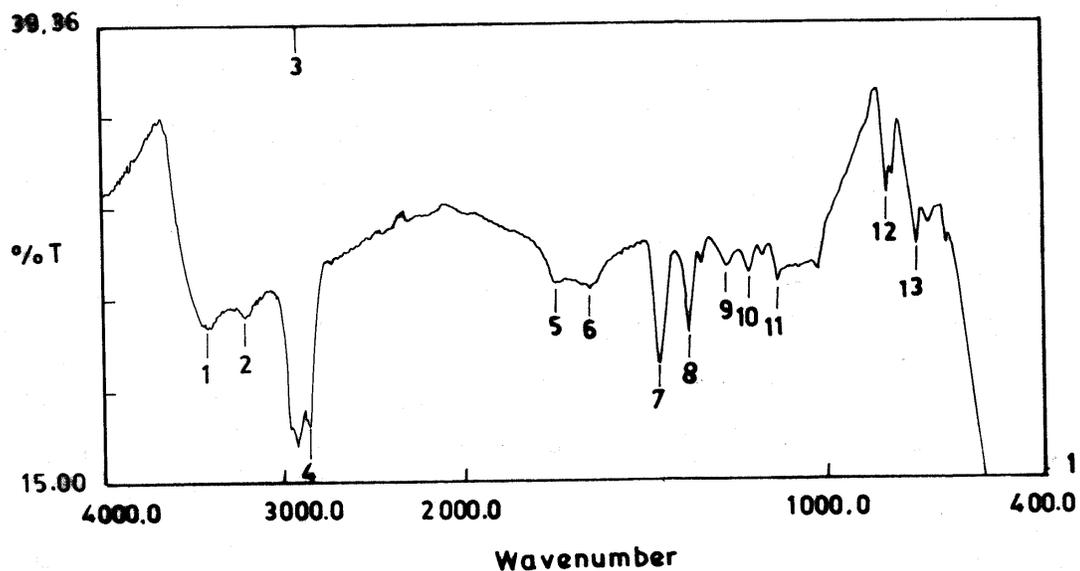
(a) KBr pellet

Recorded on Jasco FT/IR 5300 spectrometer

Peak table, cm^{-1} (% T)

1: 3462.54 (36.3)	2: 3219.48 (35.3)	3: 2363.01 (43.8)	4: 1747.66 (32.1)
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5: 1653.14 (33.4)	6: 1454.46 (36.7)	7: 1386.94 (35.1)	8: 1338.72 (36.7)
9: 1277.00 (32.7)	10: 1213.33 (33.0)	11: 1174.75 (35.7)	12: 1134.25 (31.3)
13: 831.39 (36.9)	14: 748.45 (33.7)	15: 709.87 (41.2)	16: 596.06 (41.2)
17: 547.83 (38.9)	18: 505.40 (42.9)	19: 449.45 (45.6)	



(b) Nujol mull

Recorded on Jasco FT/IR 5300 spectrometer

Peak table, cm^{-1} (% T)

1: 3423.96 (23.3)	2: 3207.91 (23.9)	3: 2922.42 (16.9)	4: 2856.83 (18.0)
5: 1741.88 (25.6)	6: 1651.22 (25.3)	7: 1458.32 (21.3)	8: 1377.30 (23.0)
9: 1273.13 (26.3)	10: 1209.48 (26.0)	11: 1132.32 (25.5)	12: 829.47 (30.1)
13: 746.52 (27.4)			

References

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