

Water-induced pseudo-quadruple hydrogen-bonding motifs in xanthine–inorganic acid complexes

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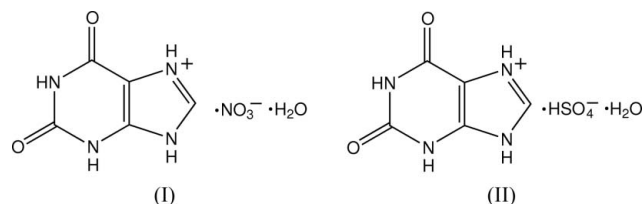
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In xanthinium nitrate hydrate [systematic name: 2,6-dioxo-1,2,3,6-tetrahydro-9*H*-purin-7-ium nitrate monohydrate], $C_5H_5N_4O_2^+ \cdot NO_3^- \cdot H_2O$, (I), and xanthinium hydrogen sulfate hydrate [systematic name: 2,6-dioxo-1,2,3,6-tetrahydro-9*H*-purin-7-ium hydrogen sulfate monohydrate], $C_5H_5N_4O_2^+ \cdot HSO_4^- \cdot H_2O$, (II), the xanthine molecules are protonated at the imine N atom with the transfer of an H atom from the inorganic acid. The asymmetric unit of (I) contains a xanthinium cation, a nitrate anion and one water molecule, while that of (II) contains two crystallographically independent xanthinium cations, two hydrogen sulfate anions and two water molecules. A pseudo-quadruple hydrogen-bonding motif is formed between the xanthinium cations and the water molecules *via* $N-H \cdots O$ and $O-H \cdots O$ hydrogen bonds in both structures, and leads to the formation of one-dimensional polymeric tapes. These cation–water tapes are further connected by the respective anions and aggregate into two-dimensional hydrogen-bonded sheets in (I) and three-dimensional arrangements in (II).

Comment

Quadruple hydrogen-bonding motifs (dimeric units held together by four hydrogen bonds between the self-complementary *DADA* arrays; *D* = donors and *A* = acceptor) have received considerable attention in recent decades due to their greater stability compared with double or triple hydrogen-bonding motifs (Beijer *et al.*, 1998). This binding pattern is widely utilized to construct dynamic supramolecular polymers (Corbin & Zimmerman, 1998, 2000). Recently, Lafitte *et al.* (2006) reported a new quadruple hydrogen-bonding module based on a ureido-substituted cytosine moiety. Xanthine (3,7-dihydropurine-2,6-dione) is a purine base found in most tissues and fluids in the human body and in other organisms. Xanthine and its nucleotide counterpart xanthosine monophosphate are important intermediates in the metabolism of purines and their nucleotides in cells. A number of mild

stimulants are derived from xanthine, including caffeine and theobromine. Xanthine exists as the 2,6-diketone tautomer at neutral pH. It can adopt 14 tautomeric forms through either keto–enol transformation or proton exchange at the ring N atoms. X-ray experiments show that the sodium salt of xanthine is found mainly in the N9-H (ammonium) dioxo tautomeric form in the solid state (Mizuno *et al.*, 1969). It was also predicted, on the basis of both semi-empirical and *ab initio* calculations, that the N7-H (iminium) dioxo tautomeric form of xanthine would be energetically favoured over the N9-H tautomer in the gas phase (Nonella *et al.*, 1993). We report here two xanthine–inorganic acid complexes, namely xanthinium nitrate hydrate, (I), and xanthinium hydrogen sulfate hydrate, (II), in continuation of our ongoing studies of hydrogen-bonded interactions and molecular recognition of nucleobases in the solid state (Sridhar & Ravikumar, 2007, 2008, 2010; Sridhar *et al.*, 2009).



In compounds (I) and (II), the bond lengths and angles (Tables 1 and 3) are all normal for their types (Allen *et al.*, 1987). The asymmetric unit of (I) contains a xanthinium cation, a nitrate anion and one water molecule (Fig. 1). In (II), the asymmetric unit contains two crystallographically independent xanthinium cations (*A* and *B*), two hydrogen sulfate anions (*A* and *B*) and two water molecules (O1*W* and O2*W*) (Fig. 2). The sulfate anions of (II) exhibit a slightly distorted tetrahedral geometry, with bond lengths and angles typical of those found in several crystal structures of this kind (Cambridge Structural Database, Version 5.32; Allen, 2002). Within the anion, the S–OH distance (Table 3) and its participation in the hydrogen bond show that the H-atom site is static, rather than mobile between the O atoms. The O–S–

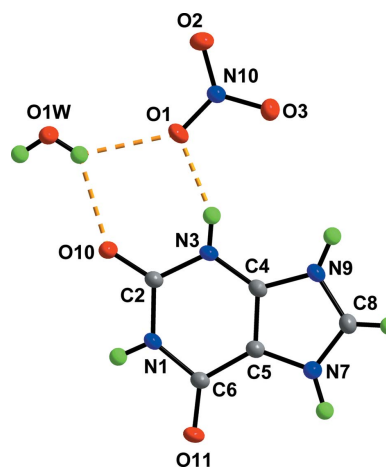


Figure 1

The molecular components of (I), showing the atom-labelling scheme. Displacement ellipsoids are drawn at the 30% probability level. Hydrogen bonds are shown as dashed lines.

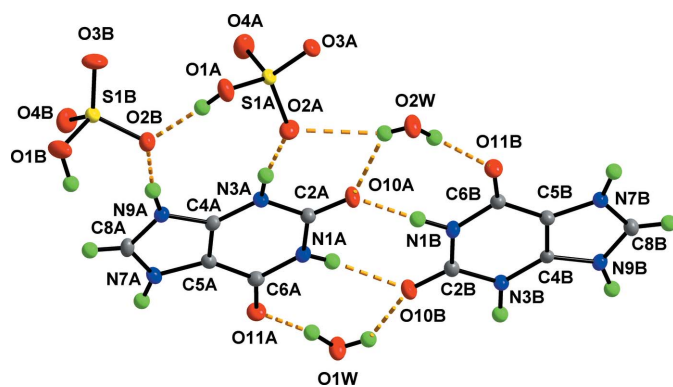


Figure 2
The molecular components of (II), showing the atom-labelling scheme. Displacement ellipsoids are drawn at the 30% probability level. Hydrogen bonds are shown as dashed lines.

O angles (Table 3) are typical of those found in hydrogen sulfate anions in crystalline salts.

As expected, xanthine forms protonated units in (I) and (II) with the transfer of an H atom from the inorganic acid. A similar situation is observed in xanthinium perchlorate dihydrate (Biradha *et al.*, 2010).

Details of the hydrogen-bonding geometries in (I) and (II) are listed in Tables 2 and 4. A number of intermolecular hydrogen bonds stabilize the crystal structure of each compound.

In (I) and (II), the xanthinium cations and water molecules are interlinked by six hydrogen bonds (two N—H···O and four O—H···O), forming a pseudo-quadruple hydrogen-bonding motif. This motif can be defined in the form of three fused $R_3^2(8)$, $R_2^2(8)$ and $R_3^3(8)$ rings (Fig. 3), in order, using graph-set notation (Etter, 1990; Etter *et al.*, 1990; Bernstein *et al.*, 1995). The xanthinium cations of (I) are held together by N—H···O hydrogen bonds, forming a centrosymmetric dimer [$R_2^2(8)$ motif]. This centrosymmetric dimer is further connected to either side of the water molecules by O—H···O hydrogen bonds [$R_3^3(8)$ motifs]. In (II), the two symmetry-

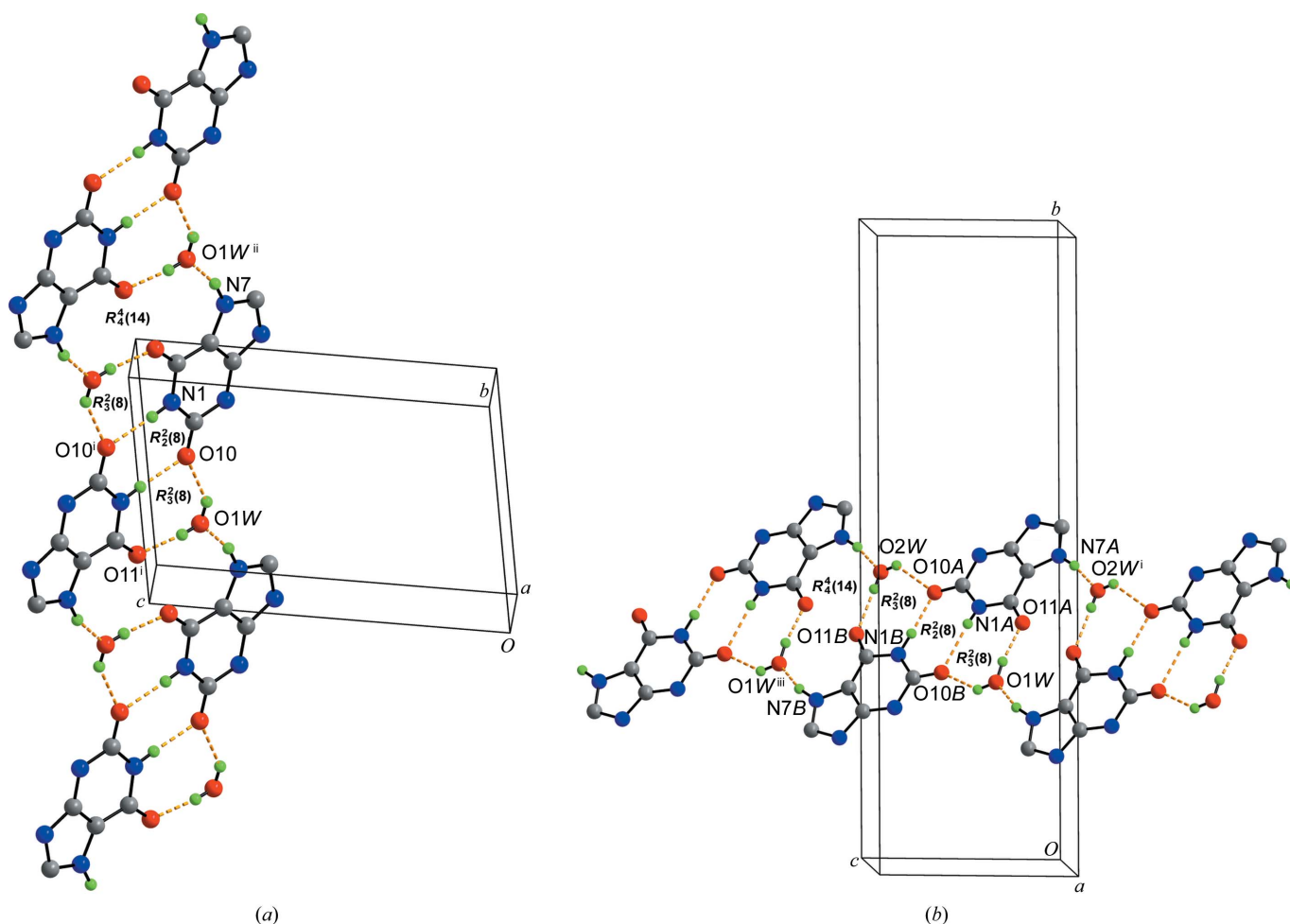


Figure 3
(a) A view of the one-dimensional polymeric tapes of (I), formed along [110] by N—H···O and O—H···O interactions involving the cations and water molecules. [Symmetry codes: (i) $-x + 2, -y + 1, -z + 2$; (ii) $x + 1, y + 1, z$.] (b) A view of the one-dimensional polymeric tapes of (II), formed along [10 $\bar{1}$] by N—H···O and O—H···O interactions involving the cations and water molecules. [Symmetry codes: (i) $x + 1, y, z - 1$; (iii) $x - 1, y, z + 1$.] For the sake of clarity, the nitrate anion in (I), the two hydrogen sulfate anions in (II) and H atoms not involved in hydrogen bonding have been omitted. Only atoms involved in hydrogen bonding are labelled.

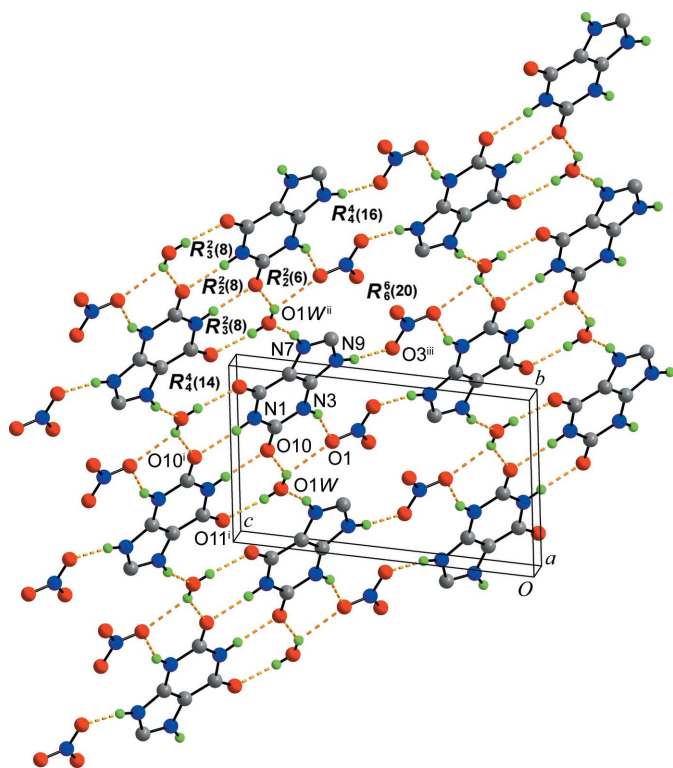


Figure 4

The crystal structure of (I), showing the two-dimensional hydrogen-bonded sheets built from cations, anions and water molecules. For the sake of clarity, H atoms not involved in hydrogen bonding have been omitted. Only atoms involved in hydrogen bonding are labelled. [Symmetry codes: (i) $-x + 2, -y + 1, -z + 2$; (ii) $x + 1, y + 1, z$; (iii) $-x + 1, -y + 2, -z + 1$.]

independent xanthinium cations are interlinked by two intermolecular N—H...O hydrogen bonds to form a noncentrosymmetric dimer, which is further linked by two water molecules through intermolecular O—H...O hydrogen bonds.

In (I), the pseudo-quadruple hydrogen-bonding motif is further connected to its translation-related motif at $(x + 1, y + 1, z)$ by an N—H...O hydrogen bond involving atom N7 of the xanthinium cation and the water molecule, producing an $R_4^4(14)$ ring motif. This N—H...O hydrogen bond leads to the formation of a one-dimensional polymeric tape parallel to the $[110]$ axis (Fig. 3*a*). Similarly, in (II), the pseudo-quadruple hydrogen-bonding motif is linked to its neighbouring motif by N—H...O hydrogen bonds [$R_4^4(14)$ motif], generating a one-dimensional polymeric tape parallel to the $[10\bar{1}]$ axis (Fig. 3*b*).

The crystal packing of (I) reveals the involvement of the nitrate anion in crosslinking the stacks of one-dimensional polymeric tapes into two-dimensional hydrogen-bonded sheets parallel to the $(1\bar{1}\bar{2})$ plane (Fig. 4). The water molecule is involved in three-centred hydrogen bonding (Jeffrey & Saenger, 1991) with the cation and anion to produce an $R_2^2(6)$ motif (Fig. 1). Each pseudo-quadruple hydrogen-bonding motif is interlinked to its inversion-related motif by intermolecular N—H...O hydrogen bonds involving atom N9 of the xanthinium cation and atom O3 of the nitrate anion. This N—H...O hydrogen bond generates a centrosymmetric

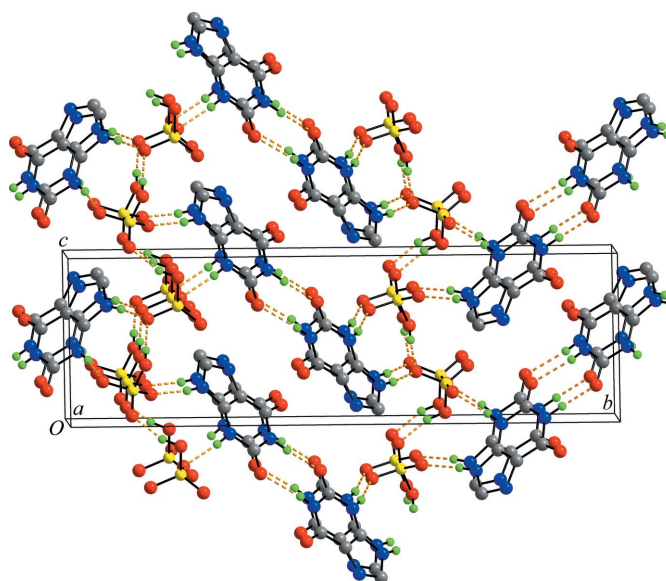


Figure 5

Part of the crystal structure of (II), showing the three-dimensional hydrogen-bonded networks formed by pairs of cation–cation dimers and the infinite anion–anion chain along the crystallographic c axis. For the sake of clarity, the two water molecules (O1W and O2W) and H atoms not involved in hydrogen bonding have been omitted.

tetramer and produces a characteristic $R_4^4(16)$ ring motif. Thus, the combination of N—H...O and O—H...O hydrogen bonds involving the xanthinium cation, nitrate anion and water molecule forms a centrosymmetric hexamer to produce another $R_6^6(20)$ ring motif and these aggregate into supramolecular two-dimensional hydrogen-bonded sheets.

In (II), the O—H...O hydrogen bonds interconnect two hydrogen sulfate anions into an $[-\text{HOSO}-\text{HOSO}-]_n$ chain along the c axis with a $C_2^2(8)$ graph set. Each anion is involved in two such hydrogen bonds, acting as an H-atom donor in one of them and as an H-atom acceptor in the other. Atoms N3A and N9A of the xanthinium cation link atoms O2A and O2B of the hydrogen sulfate chain through intermolecular N—H...O interactions, forming an $R_2^2(10)$ motif, while atoms N3B and N9B of the cation link the symmetry-related atoms O4B($-x + 3, y - \frac{1}{2}, -z + 1$) and O4A($-x + 3, y - \frac{1}{2}, -z + 2$) of the hydrogen sulfate anions to form an $R_3^3(12)$ motif. Thus, the infinite anion–anion chain along the crystallographic c axis interlinks the pairs of cation–cation dimers, leading to the formation of a three-dimensional hydrogen-bonded network (Fig. 5). The two water molecules are involved in three-centred hydrogen bonding with the cations and anions to produce an $R_2^2(8)$ motif, thus completing the three-dimensional hydrogen-bonded network (Fig. 6).

Overall, in (I), the stacking of the parallel molecular tapes is aligned parallel to the $(1\bar{1}\bar{2})$ plane, while in (II), the parallel cation–cation dimers are bridged by sulfate anions to form a three-dimensional structure. It is interesting to note that similar cation–cation dimers are observed in the structure of the dixanthinium tetrachloridozinc(II) complex (Hanggi *et al.*, 1992), in which the cation–cation dimers are bridged by $[\text{ZnCl}_4]^{2-}$ anions. Weak C—H...O interactions are also observed in both structures.

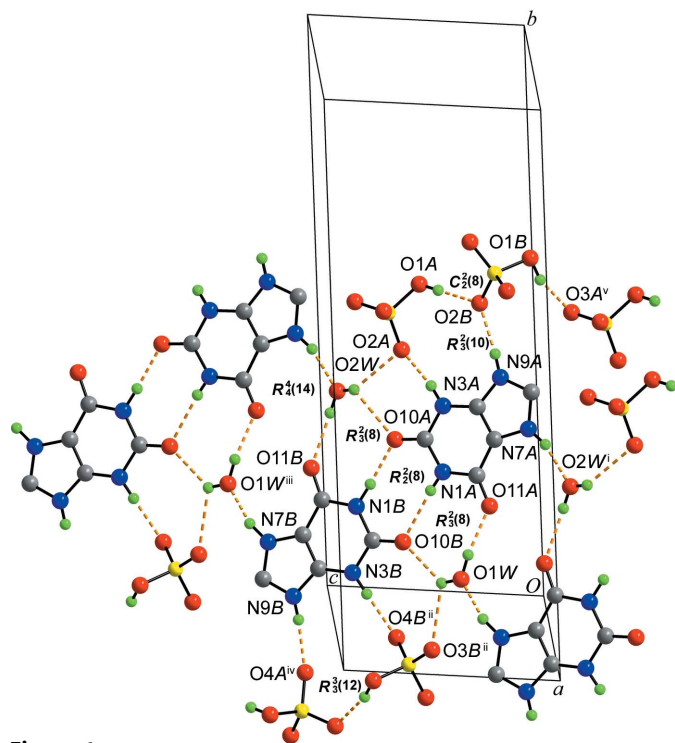


Figure 6 Part of the crystal structure of (II), showing the hydrogen-bonding interactions (dashed lines). H atoms not involved in hydrogen bonding have been omitted for clarity. [Symmetry codes: (i) $x + 1, y, z - 1$; (ii) $-x + 3, y - \frac{1}{2}, -z + 1$; (iii) $x - 1, y, z + 1$; (iv) $-x + 3, y - \frac{1}{2}, -z + 2$; (v) $x, y, z - 1$.]

Experimental

A hot aqueous solution (5 ml) of xanthine (0.150 g, 1 mmol) was mixed with either 65% nitric acid (5 ml) [for the preparation of (I)] or 98% sulfuric acid (5 ml) [for the preparation of (II)]. Crystals of both compounds were obtained from their respective solutions after several weeks by slow evaporation of the aqueous solvent at room temperature.

Compound (I)

Crystal data

$C_5H_5N_4O_2^+ \cdot NO_3^- \cdot H_2O$
 $M_r = 233.16$
 Triclinic, $P\bar{1}$
 $a = 5.0416$ (7) Å
 $b = 7.4621$ (10) Å
 $c = 12.1396$ (16) Å
 $\alpha = 80.248$ (2)°
 $\beta = 80.800$ (2)°
 $\gamma = 75.657$ (2)°
 $V = 432.74$ (10) Å³
 $Z = 2$
 Mo $K\alpha$ radiation
 $\mu = 0.16$ mm⁻¹
 $T = 294$ K
 $0.21 \times 0.18 \times 0.09$ mm

Data collection

Bruker SMART APEX CCD area-detector diffractometer
 4689 measured reflections
 1801 independent reflections
 1672 reflections with $I > 2\sigma(I)$
 $R_{int} = 0.019$

Refinement

$R[F^2 > 2\sigma(F^2)] = 0.037$
 $wR(F^2) = 0.102$
 $S = 1.15$
 1801 reflections
 169 parameters
 H atoms treated by a mixture of independent and constrained refinement
 $\Delta\rho_{max} = 0.19$ e Å⁻³
 $\Delta\rho_{min} = -0.28$ e Å⁻³

Table 1
Selected bond angles (°) for (I).

C8—N7—C5	107.89 (12)	C8—N9—C4	107.42 (12)
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Table 2
Hydrogen-bond geometry (Å, °) for (I).

<i>D</i> —H... <i>A</i>	<i>D</i> —H	H... <i>A</i>	<i>D</i> ... <i>A</i>	<i>D</i> —H... <i>A</i>
N1—H1N...O10 ⁱ	0.88 (2)	1.99 (2)	2.8761 (15)	177 (2)
N3—H3N...O1	0.85 (2)	1.97 (2)	2.7604 (17)	153 (2)
N7—H7N...O1W ⁱⁱ	0.96 (2)	1.69 (2)	2.6233 (17)	162 (2)
N9—H9N...O3 ⁱⁱⁱ	0.92 (2)	1.88 (3)	2.7878 (17)	168 (2)
O1W—H1W...O10	0.80 (3)	2.24 (3)	2.8873 (16)	139 (2)
O1W—H1W...O1	0.80 (3)	2.27 (3)	2.8986 (18)	136 (2)
O1W—H2W...O11 ⁱ	0.80 (3)	2.02 (3)	2.8059 (16)	170 (3)

Symmetry codes: (i) $-x + 2, -y + 1, -z + 2$; (ii) $x + 1, y + 1, z$; (iii) $-x + 1, -y + 2, -z + 1$.

Compound (II)

Crystal data

$C_5H_5N_4O_2^+ \cdot HSO_4^- \cdot H_2O$
 $M_r = 268.21$
 Monoclinic, $P2_1$
 $a = 5.183$ (5) Å
 $b = 24.805$ (5) Å
 $c = 7.701$ (5) Å
 $\beta = 103.510$ (5)°
 $V = 962.7$ (11) Å³
 $Z = 4$
 Mo $K\alpha$ radiation
 $\mu = 0.37$ mm⁻¹
 $T = 294$ K
 $0.18 \times 0.15 \times 0.07$ mm

Data collection

Bruker SMART APEX CCD area-detector diffractometer
 10396 measured reflections
 3998 independent reflections
 3939 reflections with $I > 2\sigma(I)$
 $R_{int} = 0.020$

Refinement

$R[F^2 > 2\sigma(F^2)] = 0.030$
 $wR(F^2) = 0.080$
 $S = 1.06$
 3998 reflections
 364 parameters
 4 restraints
 H atoms treated by a mixture of independent and constrained refinement
 $\Delta\rho_{max} = 0.46$ e Å⁻³
 $\Delta\rho_{min} = -0.34$ e Å⁻³
 Absolute structure: Flack & Bernardinelli (2000), with 1946 Friedel pairs
 Flack parameter: 0.13 (5)

Table 3
Selected geometric parameters (Å, °) for (II).

S1A—O4A	1.425 (2)	S1B—O3B	1.4148 (19)
S1A—O3A	1.4453 (17)	S1B—O4B	1.449 (2)
S1A—O2A	1.4574 (17)	S1B—O2B	1.4877 (16)
S1A—O1A	1.5504 (18)	S1B—O1B	1.5430 (19)
C8A—N7A—C5A	108.34 (17)	O3A—S1A—O1A	104.69 (12)
C8A—N9A—C4A	107.53 (18)	O2A—S1A—O1A	105.62 (11)
C8B—N7B—C5B	107.72 (18)	O3B—S1B—O4B	116.08 (13)
C8B—N9B—C4B	107.56 (17)	O3B—S1B—O2B	113.06 (12)
O4A—S1A—O3A	114.17 (12)	O4B—S1B—O2B	108.30 (11)
O4A—S1A—O2A	112.27 (13)	O3B—S1B—O1B	105.74 (13)
O3A—S1A—O2A	110.13 (10)	O4B—S1B—O1B	108.26 (13)
O4A—S1A—O1A	109.33 (11)	O2B—S1B—O1B	104.67 (11)

Table 4
Hydrogen-bond geometry (Å, °) for (II).

<i>D</i> —H... <i>A</i>	<i>D</i> —H	H... <i>A</i>	<i>D</i> ... <i>A</i>	<i>D</i> —H... <i>A</i>
N1A—H1N...O10B	0.83 (3)	2.12 (3)	2.949 (2)	173 (2)
N3A—H2N...O2A	0.88 (3)	1.83 (3)	2.703 (3)	169 (3)
N7A—H3N...O2W ⁱ	0.85 (2)	1.89 (2)	2.710 (3)	162 (4)
N9A—H4N...O2B	0.86 (3)	1.96 (3)	2.799 (3)	166 (2)
N1B—H5N...O10A	0.97 (4)	1.84 (4)	2.814 (2)	177 (3)
N3B—H6N...O4B ⁱⁱ	0.90 (3)	1.93 (3)	2.795 (3)	163 (2)
N7B—H7N...O1W ⁱⁱⁱ	0.97 (3)	1.70 (3)	2.657 (3)	167 (3)
N9B—H8N...O4A ^{iv}	0.84 (2)	1.91 (2)	2.739 (3)	173 (3)
O1A—H1O...O2B	0.81 (2)	1.81 (2)	2.618 (3)	177 (3)
O1B—H2O...O3A ^v	0.86 (5)	1.78 (5)	2.597 (2)	157 (4)
O1W—H1W...O11A	0.90 (3)	1.88 (3)	2.769 (3)	169 (3)
O1W—H2W...O10B	0.79 (4)	2.40 (4)	2.992 (3)	133 (4)
O1W—H2W...O3B ⁱⁱ	0.79 (4)	2.49 (4)	2.897 (3)	114 (4)
O2W—H3W...O2A	0.74 (5)	2.36 (5)	3.016 (3)	149 (4)
O2W—H3W...O10A	0.74 (5)	2.57 (5)	3.092 (3)	130 (4)
O2W—H4W...O11B	0.79 (4)	2.08 (4)	2.867 (3)	174 (4)

Symmetry codes: (i) $x + 1, y, z - 1$; (ii) $-x + 3, y - \frac{1}{2}, -z + 1$; (iii) $x - 1, y, z + 1$; (iv) $-x + 3, y - \frac{1}{2}, -z + 2$; (v) $x, y, z - 1$.

N-bound H atoms of the xanthinium cations of (I) and (II), O-bound H atoms of the hydrogen sulfate anion of (II) and H atoms of the water molecules of (I) and (II) were located in difference Fourier maps and their positions and isotropic displacement parameters refined. All other H atoms were located in difference density maps, positioned geometrically and included as riding atoms, with $C-H = 0.93 \text{ \AA}$ and $U_{iso}(H) = 1.2U_{eq}(C)$. For (II), distance restraints were applied with a set value of $0.87 (2) \text{ \AA}$ for N7A—H3N and N9B—H8N, and $0.82 (2) \text{ \AA}$ for O1A—H1O. Compound (II) crystallizes in the noncentrosymmetric space group $P2_1$ but the structure shows pseudosymmetry, which is fulfilled for approximately 82% of the atoms. Systematic absences show the space group to be $P2_1/c$, even though the absence condition for a c -glide is not strictly satisfied. The structure was solved in both the $P2_1$ and $P2_1/c$ space groups. However, the structure refined in the space group $P2_1/c$ showed poor residual factors and abnormal geometric parameters, while the structure refined in the space group $P2_1$ did not show such problems. The asymmetric unit of (II) also does not show any inversion centre between the sulfate ions. Refinement in a higher symmetric space group is not possible. The value of the Flack parameter (Flack & Bernardinelli, 2000) of (II) may be indicative of a small amount of inversion twinning, although the precision of the value does not allow any definitive conclusion to be drawn.

For both compounds, data collection: *SMART* (Bruker, 2001); cell refinement: *SAINT* (Bruker, 2001); data reduction: *SAINT*; program(s) used to solve structure: *SHELXS97* (Sheldrick, 2008); program(s) used to refine structure: *SHELXL97* (Sheldrick, 2008); molecular graphics: *DIAMOND* (Brandenburg & Putz, 2005); software used to prepare material for publication: *SHELXL97*.

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Supplementary data for this paper are available from the IUCr electronic archives (Reference: DN3164). Services for accessing these data are described at the back of the journal.

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