Structure of the β form of calcium pyrophosphate tetrahydrate

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β-$Ca_2P_2O_7 \cdot 4H_2O$ is monoclinic, $P2_1/c$, $a = 12.287$ (6), $b = 7.511$ (3), $c = 10.775$ (5) Å, and $\beta = 112.54$ (1)°. Five of the terminal O atoms from a pyrophosphate group bind to Ca atoms, together with O atoms from three of the water molecules. The fourth H_2O forms only hydrogen bonds. Both Ca atoms have coordination number 7 and show characteristics between those of a capped octahedron and a pentagonal bipyramid. The analysis of coordination distortions suggests that regularity and volume efficiency of a Ca coordination polyhedron increases with the number of bound water O atoms. The structure is layered after {100}, reflected also in the morphology of crystals which are formed as extremely thin plates. The central parts of the layers are formed by chains of Ca coordination polyhedra which run along the b axis and are interconnected by pyrophosphate groups. Water molecules form the surfaces of the layers. A peculiar auto-inhibition of growth from supersaturated solutions is supposed to be caused by a direct attachment of $CaP_2O_7^{2-}$ and $P_2O_7^{4-}$ to the water molecules on the surfaces of layers. $Ca_2P_2O_7 \cdot 4H_2O$ is known in two polymorphs. The unit-cell volume of the β form compared with that of α suggests that the former is a low-temperature modification.

1. Introduction

Deposition of calcium pyrophosphate dihydrate crystals, $Ca_2P_2O_7 \cdot 2H_2O$, in articular cartilage and their shedding into synovia is a common cause of pain in the joints of aged humans. The crystals exist in at least two polymorphs, one triclinic (denoted t-CPPD) with known structure (Mandel, 1975) and the other supposedly monoclinic (denoted m-CPPD; Brown *et al.*, 1963; Mandel *et al.*, 1988). Both forms have been observed *in vivo* (Pritzker, 1998). The existence of a third, hexagonal polymorph prepared *in vitro* was also suggested (Mandel *et al.*, 1988). Besides t- and m-CPPD, a tetrahydrate, $Ca_2P_2O_7 \cdot 4H_2O$ (denoted CPPT) is common in precipitates formed *in vitro* around neutral and acidic pH. The tetrahydrate is also polymorphic, with one monoclinic form with a known structure (Davis *et al.*, 1985) and another form previously supposed to be orthorhombic from the microscopic investigation of crystal morphology (Brown *et al.*, 1963) and indexing of powder patterns (Mandel *et al.*, 1988). However, the present study shows this form to be monoclinic as well, but even if the space group is the same the structures are largely different. Since both forms are monoclinic, the previously used notations m-CPPT and o-CPPT should be abandoned and we propose to denote them m-CPPTα and m-CPPTβ, respectively.

Table 1
Experimental details.

Crystal data	
Chemical formula	$Ca_2P_2O_7 \cdot 4H_2O$
Chemical formula weight	326.16
Cell setting	Monoclinic
Space group	$P2_1/c$
a (Å)	12.287 (6)
b (Å)	7.511 (3)
c (Å)	10.775 (5)
β (°)	112.542 (14)
V (Å^3)	918.4 (7)
Z	4
D_x (Mg m^{-3})	2.359
Radiation type	Mo $K\alpha$
Wavelength (Å)	0.71073
No. of reflections for cell parameters	173
μ (mm^{-1})	1.639
Temperature (K)	298 (2)
Crystal form	{100},{001},{011}
Crystal size (mm)	$0.243 \times 0.055 \times 0.009$
Crystal colour	Colourless
Data collection	
Absorption correction	Gaussian face-indexed
T_{min}	0.89064
T_{max}	0.98700
No. of measured reflections	2928
No. of independent reflections	959
No. of observed reflections	432
Criterion for observed reflections	$I > 2\sigma(I)$
R_{int}	0.2569
θ_{max} (°)	20.80
Range of h, k, l	$-11 \rightarrow h \rightarrow 12$
	$-5 \rightarrow k \rightarrow 7$
	$-10 \rightarrow l \rightarrow 9$
Refinement	
Refinement on	F^2
$R[F^2>2\sigma(F^2)]$	0.0695
$wR(F^2)$	0.1651
S	0.874
No. of reflections used in refinement	959
No. of parameters used	81
Weighting scheme	$w = 1/[\sigma^2(F_o^2) + (0.0459P)^2]$, where $P = (F_o^2 + 2F_c^2)/3$
$(\Delta/\sigma)_{max}$	0.012
$\Delta\rho_{max}$ (e Å^{-3})	0.697
$\Delta\rho_{min}$ (e Å^{-3})	-0.679
Extinction method	None
Source of atomic scattering factors	*International Tables for Crystallography* (1992, Vol. C, Tables 4.2.6.8 and 6.1.1.4)
Computer programs	
Structure solution	*SHELXS*97 (Sheldrick, 1990)
Structure refinement	*SHELXL*97 (Sheldrick, 1997)

In the present article the crystal structure of the β form of calcium pyrophosphate tetrahydrate is described. The preparation of crystals large enough for the single-crystal study and growth experiments on this phase showing an interesting auto-inhibition behaviour are described elsewhere (Christoffersen *et al.*, 2000). The experimental X-ray powder diffraction pattern from the precipitates as well as that calculated from the crystal structure are identical to that reported in the literature for a phase previously denoted *o*-CPPT.

Table 2
Fractional atomic coordinates and equivalent isotropic displacement parameters (Å^2).

$$U_{eq} = (1/3)\Sigma_i\Sigma_j U^{ij}a^ia^j\mathbf{a}_i.\mathbf{a}_j.$$

	x	y	z	U_{eq}
Ca1	0.4691 (3)	0.0022 (5)	0.7271 (4)	0.0174 (11)
Ca2	0.2613 (4)	0.1473 (5)	0.3157 (4)	0.0202 (12)
P1	0.7424 (5)	0.0268 (6)	0.9849 (5)	0.0179 (14)
P2	0.5607 (5)	0.2385 (7)	0.5199 (5)	0.0207 (15)
O1	0.5129 (10)	0.2410 (14)	0.1263 (10)	0.013 (3)
O2	0.4707 (10)	0.2434 (14)	0.8748 (10)	0.010 (3)
O3	0.6795 (10)	0.0141 (15)	0.8352 (10)	0.018 (3)
O4	0.2187 (11)	0.1544 (16)	0.9504 (11)	0.027 (4)
O5	0.6512 (10)	0.0938 (13)	0.0491 (11)	0.014 (3)
O6	0.6311 (10)	0.0693 (14)	0.5232 (11)	0.019 (3)
O7	0.8390 (11)	0.1595 (17)	0.0257 (12)	0.033 (4)
OW1	0.2649 (11)	0.0895 (14)	0.6711 (12)	0.026 (4)
OW2	0.8827 (12)	0.0078 (18)	0.6201 (13)	0.045 (4)
OW3	0.0776 (11)	0.1621 (17)	0.1167 (11)	0.035 (4)
OW4	0.8928 (12)	0.1621 (17)	0.3290 (12)	0.038 (4)

2. Experimental

The crystal studied was regularly developed with crystal forms {100}, {001} and {011}. The dimensions were 0.243 mm along the *b* axis, 0.055 mm along the *c* axis and 0.009 mm perpendicular to (100). Other crystal and measurement data are given in Table 1.[1] Owing to the small size no significant diffraction could be registered below 1.0 Å. This imposes a limit on the precision of the structure parameters and prohibited an accurate determination of hydrogen positions.

The reciprocal lattice was shown to have a monoclinic symmetry. Systematic extinctions are consistent with the space

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[1] Supplementary data for this paper are available from the IUCr electronic archives (Reference: OS0054). Services for accessing these data are described at the back of the journal.
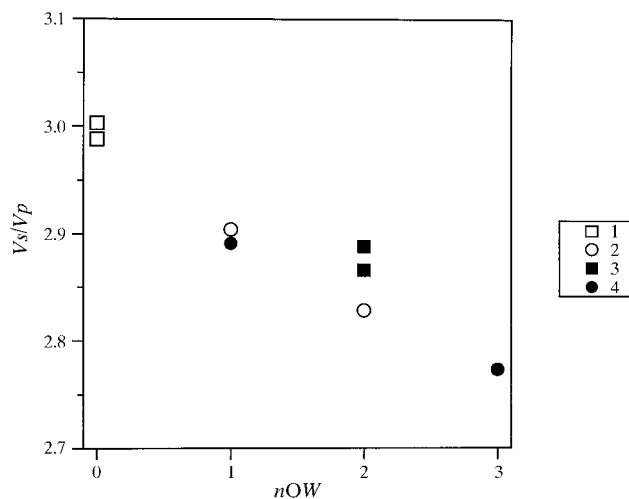

Figure 1
The relation between the number of bonded water O atoms (*n*OW) and the V_S/V_P ratio for the Ca coordination polyhedra with CN7. The coordinations are from: 1 β-Ca$_2$P$_2$O$_7$ (Webb, 1966); 2 *t*-CPPD (Mandel, 1975); 3 *m*-CPPTα (Davis *et al.*, 1985); 4 *m*-CPPTβ (this article).
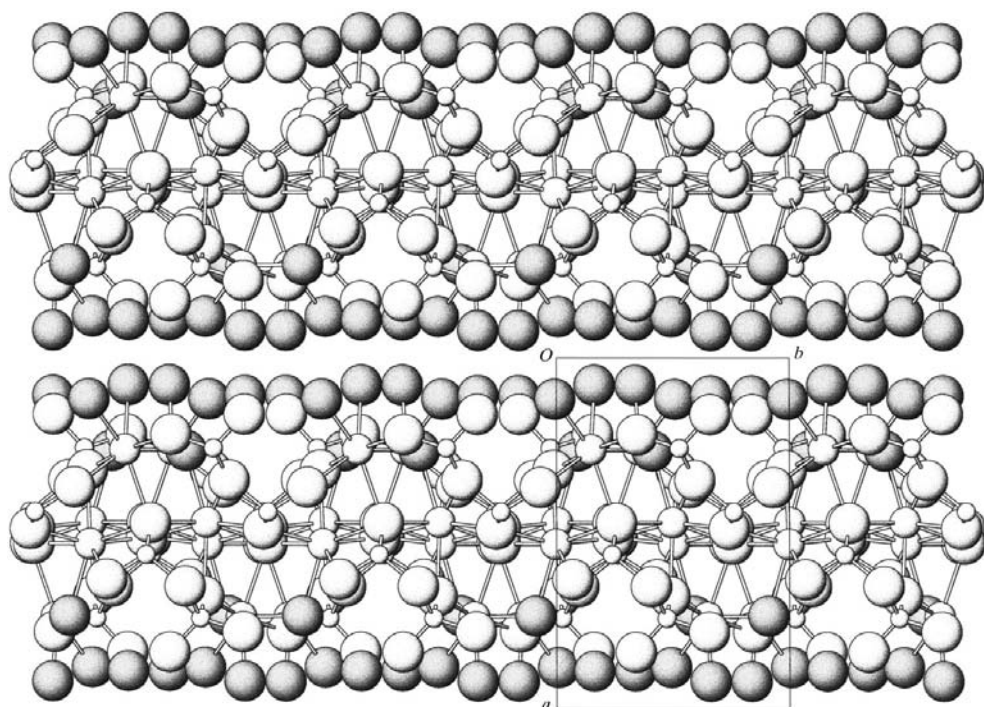
Figure 2
The crystal structure viewed along [001]. Atoms in ascending size: P, Ca, O. Darker colouring for water O atoms.
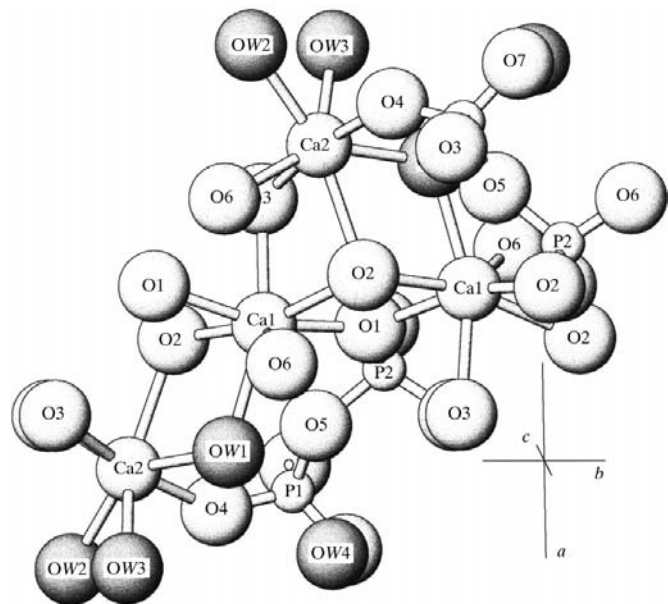

Figure 3
Details of atom coordinations with atom labels. View slightly inclined to that of Fig. 2.

group $P2_1/c$. The structure was solved by the vector superposition of Patterson maps. The result revealed the positions of the Ca and P atoms together with one O atom. In subsequent difference Fourier syntheses the remaining O atoms were located. Four of them not belonging to the pyrophosphate group are attributed to water molecules. Anisotropic

displacement factors were applied to the Ca and P atoms, while they were held isotropic for the O atoms.

The final atomic parameters are given in Table 2.

3. Structure description

Four of the O atoms in the asymmetric unit are not bound to P and are supposed to be water O atoms. Owing to the low resolution of the obtainable data it was not possible to locate H atoms reliably from the difference Fourier map. The hydrogen bonds are supposed to be oriented towards the closely situated other water O atoms or 'underbonded' O atoms from the pyrophosphate groups (see later).

Bond distances, angles and distortion parameters for Ca and P coordination polyhedra were calculated using the program *IVTON* (Balić-Žunić & Vicković, 1996) are listed in Table 3.
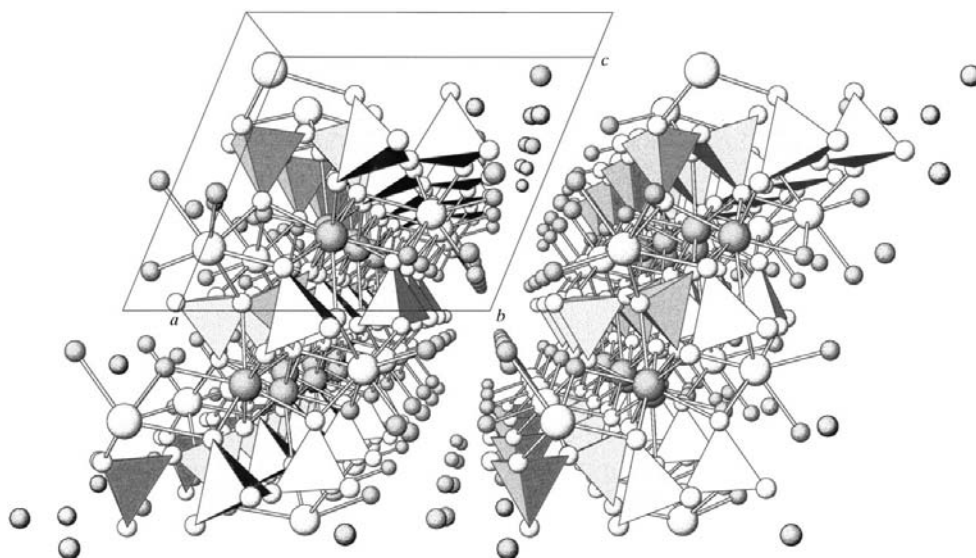
The pyrophosphate anion has general characteristics similar to the other two known calcium pyrophosphate hydrate structures (Mandel, 1975; Davis *et al.*, 1985). $P-O_B$ distances are significantly longer than $P-O_T$ and the $P-O_B-P$ angle of 134° is relatively small (B denotes bridging, and T terminal). O atoms are situated at the vertices of the almost ideal tetrahedra surrounding the P atoms. The polyhedral volume distortions (Makovicky & Balić-Žunić, 1998) are under 1% when compared to an ideal tetrahedron. The only significant coordination distortion is the eccentricity of P atoms which move away from O_B. Compared with the other two structures the main distinction is a smaller volume of the one tetrahedron (P1), most probably caused by a relatively short P1—O7 bond.[2] O7, which is a terminal atom, is not bound to any Ca while in the other two structures only the bridging O atoms do not bind to any Ca.

The Ca atoms are seven-coordinated, as in the other two known calcium pyrophosphate hydrate structures. According to the coordination parameters (Table 3), they can be regarded as either distorted pentagonal bipyramids or distorted capped octahedra. The two coordination modes in *t*-CPPD were already described as these two distinct types (Mandel, 1975). The values of V_S/V_P (ratio of volumes of the circumscribed sphere and the polyhedron) for the ideal pentagonal bipyramid and the capped octahedron are 2.6427 and 3.0491, respectively (Makovicky & Balić-Žunić, 1998).

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[2] The volumes of PO_4 tetrahedra in *t*-CPPD and α-CPPT are in the range 1.85–1.88 Å³.
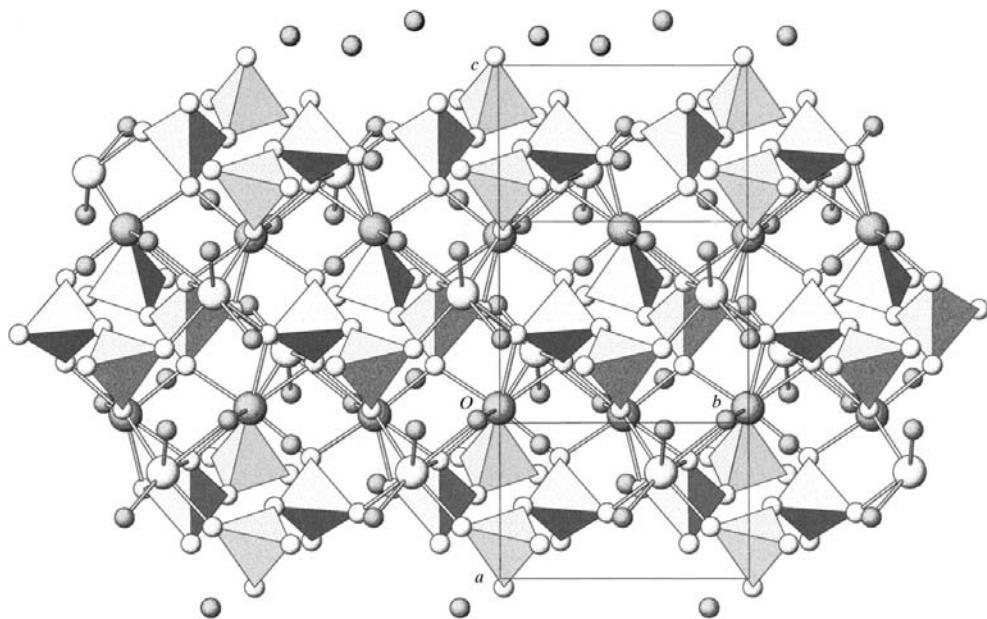
Figure 4
One structural layer projected on (100). Pyrophosphate groups represented as opaque polyhedra. Ca1 as well as water O atoms are coloured darker. The projection is bounded by the crystal forms {001} and {011}.

Figure 5
A perspective view of the crystal structure along [010]. Description of atoms as for Fig. 4.

of changing the coordination type from a capped octahedron to a pentagonal bipyramid with increasing the number of water O atoms bound to the Ca atom. In the present case Ca1 approaches the former type, while Ca2 is closest to the latter one among all calcium pyrophosphate structures.

In Fig. 2 a projection of the crystal structure parallel to [001] is shown and here the main characteristic of the structure, the layers formed of the chains of Ca coordination polyhedra interconnected by pyrophosphate groups, can be seen, while Fig. 3 gives a close look at atomic coordinations approximately along the same direction. In Fig. 4 one structural layer is projected on (100). Fig. 5 is a perspective side-view of the (100) layers in the structure.

Ca1 coordination polyhedra mutually share O1—O2 edges and form chains parallel to [010]. The neighbouring Ca1 polyhedra in a chain are further connected through Ca2 atoms which bind to the edge O2 atoms and bridge the terminal O3 and OW1 atoms. The chains are formed around the 2_1 axes and the Ca2 coordination polyhedra are in an alternate side-attachment to them. Looking along [001] the pyrophosphate groups can be found situated along the chains between the Ca2 polyhedra and aligned alternately parallel to [110] and [$\bar{1}$10]. They lie between and connect the neighbouring chains, which lie c/2 apart and are mirror-related to each other by the c-glide plane.

The OW1 atoms are shared by both Ca1 and Ca2 polyhedra and reside relatively deep inside the layers. Remaining water O atoms are situated on the surfaces of layers. OW2 and OW3 are bound to Ca2, while the OW4 atoms do not come close to any Ca atom. The O7 terminal atoms from the pyrophosphate groups, which also do not bind to any Ca, reside on the surfaces of layers as well. The surfaces of the neighbouring layers match. The OW3 atoms which protrude furthest from the surface of one layer face O7 atoms (distance 2.71 Å), which sit deepest on the surface of the neighbouring layer.

The values for the seven-coordinated Ca in calcium pyrophosphates lie between these two and the coordinations can therefore be described as transitional between the two types mentioned.[3] It can be seen from Fig. 1 that there is a tendency

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[3] The values for the coordination polyhedra which are transitional between the two types should lie between them. If the tetragonal faces of the capped octahedron (also called 'split' octahedron) break into two pairs of triangular faces, the V_S/V_P value will decrease and approach the value for the pentagonal bipyramid as the polyhedron approaches its shape. The lowest possible value is that of a regular bipyramid, which is the 'largest-volume' polyhedron for the CN7.

Table 3
The coordinations of Ca and P.

The values in diagonals (bold) are the central atom–ligand distances, in the upper-right triangle the bond angles and in the lower left the ligand–ligand distances are given. Δ = eccentricity (Å); r_S = radius of sphere fitted to ligands (Å); V_S = sphere volume (Å^3); σ = sphericity; V_P = volume of coordination polyhedron (Å^3); υ = volume distortion. σ for CN4 is 1 by definition. For explanations, see Balić-Žunić & Makovicky (1996) and Makovicky & Balić-Žunić (1998).

	O1	O1	O3	O2	OW1	O2	O6
Ca1							
O1	**2.37 (1)**	162.1 (2)	84.1 (4)	99.5 (4)	101.4 (4)	73.9 (4)	115.2 (4)
O1	4.68 (1)	**2.37 (1)**	78.5 (4)	75.2 (4)	93.5 (4)	106.0 (4)	77.9 (4)
O3	3.19 (1)	3.02 (1)	**2.40 (1)**	85.2 (4)	158.1 (4)	78.2 (4)	120.9 (4)
O2	3.64 (1)	2.92 (1)	3.25 (1)	**2.41 (1)**	73.0 (4)	162.6 (2)	137.3 (4)
OW1	3.72 (1)	3.50 (1)	4.74 (1)	2.88 (1)	**2.44 (1)**	123.7 (4)	76.2 (4)
O2	2.92 (1)	3.88 (1)	3.08 (1)	4.83 (1)	4.33 (1)	**2.48 (1)**	58.2 (4)
O6	4.16 (1)	3.10 (1)	4.31 (1)	4.62 (1)	3.08 (1)	2.45 (1)	**2.56 (1)**

Δ = 0.088; r_S = 2.429; V_S = 60.024; σ = 0.9842; V_P = 20.763; υ = 0.0859.

	O4	O3	O6	OW2	OW3	OW1	O2
Ca2							
O4	**2.28 (1)**	169.8 (4)	100.5 (4)	76.2 (4)	99.7 (4)	86.8 (4)	95.0 (4)
O3	4.61 (1)	**2.36 (1)**	85.4 (4)	113.6 (4)	81.0 (4)	83.9 (4)	77.8 (4)
O6	3.58 (1)	3.21 (1)	**2.38 (1)**	74.1 (4)	137.6 (4)	148.1 (4)	79.1 (4)
OW2	2.91 (1)	4.01 (1)	2.90 (1)	**2.43 (1)**	75.1 (4)	137.5 (4)	149.6 (4)
OW3	3.61 (1)	3.12 (1)	4.50 (1)	2.98 (1)	**2.45 (1)**	69.7 (4)	135.3 (4)
OW1	3.31 (1)	3.27 (1)	4.72 (1)	4.62 (1)	2.84 (1)	**2.53 (1)**	69.3 (4)
O2	3.55 (1)	3.08 (1)	3.13 (1)	4.79 (1)	4.61 (1)	2.88 (1)	**2.54 (1)**

Δ = 0.076; r_S = 2.419; V_S = 59.311; σ = 0.9672; V_P = 21.391; υ = 0.0469.

	O7	O3	O4	O5
P1				
O7	**1.48 (1)**	112.6 (7)	113.0 (7)	105.9 (7)
O3	2.48 (1)	**1.50 (1)**	112.2 (7)	109.0 (7)
O4	2.50 (1)	2.51 (1)	**1.52 (1)**	103.4 (6)
O5	2.47 (1)	2.53 (1)	2.45 (1)	**1.61 (1)**

Δ = 0.085; r_S = 1.526; V_S = 14.875; V_P = 1.820; υ = 0.0013.

	O1	O6	O2	O5
P2				
O1	**1.48 (1)**	117.2 (7)	115.7 (7)	102.3 (7)
O6	2.57 (1)	**1.53 (1)**	106.1 (7)	107.4 (7)
O2	2.56 (1)	2.45 (1)	**1.54 (1)**	107.4 (7)
O5	2.43 (1)	2.55 (1)	2.55 (1)	**1.63 (1)**

Δ = 0.096; r_S = 1.542; V_S = 15.356; V_P = 1.871; υ = 0.0058.

$OW4$ atoms do not coordinate any Ca atom and are thus held in the structure solely by hydrogen bonding to other O atoms. This specific nature of a quarter of the water molecules in the structure is also confirmed by thermal analysis, which showed the loss of one H_2O already below 353 K (Christoffersen *et al.*, 2000).

The extremely layered character of the structure explains well the platy morphology of the crystals after {100}. The preference for the other two often observed forms ({001} and {011}) can be connected to the ordering of pyrophosphate groups in the structure (Fig. 4).

The observed auto-inhibition of growth at increased concentrations of $CaP_2O_7^{2-}$ and $P_2O_7^{4-}$ in solution (Christoffersen *et al.*, 2000) could be explained assuming that one or probably both of these ions preferentially attach to the water O atoms with not completely saturated hydrogen bonds on the surfaces of layers, thus disturbing the normal formation of subsequent layers. As electron microscopy photographs show, at such supersaturation conditions small, extremely thin, bended and irregular primary crystals form from the solution, but the growth of the large seed crystals is inhibited (Christoffersen *et al.*, 2000).

The β-polymorph of the calcium pyrophosphate tetrahydrate thus shows a largely different structure from the α-polymorph (Davis *et al.*, 1985), although both have the same space-group symmetry. The structure of the former is a distinctly layered one with only the hydrogen bonds between the layers, while α is characterized by a three-dimensional framework structure with the water molecules inside the channels formed by calcium pyrophosphate polyhedra structure. While all water O atoms in the α form bind to Ca atoms, one in the β form is held in the structure only by hydrogen bonds. The β polymorph has a smaller unit-cell volume (5%) and could therefore represent a low-temperature form.

$OW2$ and $OW4$, which have equal medium heights on the surfaces face each other on neighbouring layers (distance 2.90 Å). These closest approaches of O atoms from the neighbouring layers fall into the category of possible hydrogen bonds. The other potential hydrogen bonds can be connected to the contacts of water O atoms inside a layer, mutual or with atoms O4, O6 and O7. The bond-valence calculations (Brown & Altermatt, 1985; Brese & O'Keeffe, 1991) give 'underbonded' values for the latter of 1.69, 1.76 and 1.39, respectively, without hydrogen-bond contributions. As mentioned before, the quality of data did not allow the determination of hydrogen positions and the detailed hydrogen-bonding scheme could not be defined.

References

Balić-Žunić, T. & Makovicky, E. (1996). *Acta Cryst.* B**52**, 78–81.
Balić-Žunić, T. & Vicković, I. (1996). *J. Appl. Cryst.* **29**, 305–306.
Brese, N. E. & O'Keeffe, M. (1991). *Acta Cryst.* B**47**, 192–197.

research papers

Brown, I. D. & Altermatt, D. (1985). *Acta Cryst.* B**41**, 244–247.

Brown, E. H., Lehr, J. R., Smith, J. P. & Frazier, A. W. (1963). *Agric. Food Chem.* **11**, 214–222.

Christoffersen, M. R., Balić-Žunić, T., Pehrson, S. & Christoffersen, J. (2000). *J. Cryst. Growth*, **212**, 500–506.

Davis, N. L., Mandel, G. S., Mandel, N. S. & Dickerson, R. E. (1985). *J. Crystallogr. Spectrosc. Res.* **15**, 513–521.

Makovicky, E. & Balić-Žunić, T. (1998). *Acta Cryst.* B**54**, 766–773.

Mandel, G. S., Renne, K. M., Kolbach, A. M., Kaplan, W. D., Miller, J. D. & Mandel, N. S. (1988). *J. Cryst. Growth*, **87**, 453–462.

Mandel, N. S. (1975). *Acta Cryst.* B**31**, 1730–1734.

Pritzker, K. P. H. (1998). *Calcium Phosphates in Biological and Industrial Systems*, edited by Z. Amjad, pp. 277–300. Boston: Kluwer Academic Publishers.

Sheldrick, G. M. (1990). *Acta Cryst.* A**46**, 467–473.

Sheldrick, G. M. (1997). *SHELXTL Program Manual*. Bruker AXS.

Webb, N. C. (1966). *Acta Cryst.* **21**, 942–948.