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An orthorhombic polymorph of cerium(III) ultraphosphate,  $\text{CeP}_5\text{O}_{14}$ Jing Zhu,<sup>a\*</sup> Wen-Dan Cheng<sup>b</sup> and Hao Zhang<sup>b</sup>

<sup>a</sup>Department of Material Science and Engineering, Yunnan University, Kunming, Yunnan 650091, People's Republic of China, and <sup>b</sup>State Key Laboratory of Structural Chemistry, Fujian Institute of Research on the Structure of Matter, Chinese Academy of Sciences, Fuzhou, Fujian 350002, People's Republic of China  
Correspondence e-mail: jzhu@ynu.edu.cn

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Key indicators: single-crystal X-ray study;  $T = 293$  K; mean  $\sigma(\text{P}-\text{O}) = 0.007$  Å;  $R$  factor = 0.048;  $wR$  factor = 0.094; data-to-parameter ratio = 12.7.

Cerium(III) ultraphosphate,  $\text{CeP}_5\text{O}_{14}$ , was synthesized by a high-temperature solution reaction between  $\text{CeO}_2$  and  $\text{NH}_4\text{H}_2\text{PO}_4$  in a Ce–P molar ratio of 1:12. Colourless crystals of the orthorhombic polymorph were obtained by cooling the melt of the mixture. The structure contains  $(\text{P}_5\text{O}_{14})^{3-}$  anionic ribbons linked by distorted  $\text{CeO}_8$  polyhedra.

## Related literature

For applications of rare-earth ultraphosphates, see: Cole *et al.* (2000); Katrusiak & Kaczmarek (1995); Kobayashi *et al.* (1976); Schulz *et al.* (1974). For a discussion of structure types in this chemical system, see: Averbuch-Pouchot & Durif (1992). For the triclinic polymorph of  $\text{CeP}_5\text{O}_{14}$ , see: Rzaigui *et al.* (1984).

## Experimental

## Crystal data

$\text{CeP}_5\text{O}_{14}$	$V = 1047.97$ (18) Å <sup>3</sup>
$M_r = 518.97$	$Z = 4$
Orthorhombic, $Pmna$	Mo $K\alpha$ radiation
$a = 13.1252$ (12) Å	$\mu = 5.19$ mm <sup>-1</sup>
$b = 8.7991$ (9) Å	$T = 293$ (2) K
$c = 9.0741$ (9) Å	$0.08 \times 0.08 \times 0.05$ mm

## Data collection

Rigaku Mercury CCD diffractometer	7608 measured reflections
Absorption correction: multi-scan ( <i>CrystalClear</i> ; Molecular Structure Corporation & Rigaku, 2001)	1262 independent reflections
$T_{\min} = 0.663$ , $T_{\max} = 0.771$	1212 reflections with $I > 2\sigma(I)$
	$R_{\text{int}} = 0.072$

## Refinement

$R[F^2 > 2\sigma(F^2)] = 0.048$	99 parameters
$wR(F^2) = 0.094$	$\Delta\rho_{\text{max}} = 1.70$ e Å <sup>-3</sup>
$S = 1.00$	$\Delta\rho_{\text{min}} = -1.08$ e Å <sup>-3</sup>
1262 reflections	

Data collection: *CrystalClear* (Molecular Structure Corporation & Rigaku, 2001); cell refinement: *CrystalClear*; data reduction: *CrystalClear*; program(s) used to solve structure: *SHELXS97* (Sheldrick, 2008); program(s) used to refine structure: *SHELXL97* (Sheldrick, 2008); molecular graphics: *SHELXTL* (Sheldrick, 2008) and *DIAMOND* (Brandenburg, 2005); software used to prepare material for publication: *SHELXL97*.

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Supplementary data and figures for this paper are available from the IUCr electronic archives (Reference: B12303).

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## supporting information

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## An orthorhombic polymorph of cerium(III) ultraphosphate, $\text{CeP}_5\text{O}_{14}$

Jing Zhu, Wen-Dan Cheng and Hao Zhang

### S1. Comment

Rare-earth ultraphosphates,  $\text{LnP}_5\text{O}_{14}$  (Ln = rare-earth element), have attracted wide interest because of their potential applications in the laser domain (Schulz *et al.*, 1974; Kobayashi *et al.*, 1976; Katrusiak & Kaczmarek, 1995; Cole *et al.*, 2000). These compounds can be generally classified into four structure types: monoclinic ( $P2_1/a$ ), monoclinic ( $C2/c$ ), orthorhombic ( $Pnma$ ), and triclinic ( $P1$ ) (Averbuch-Pouchot & Durif, 1992). In this chemical system, many of the compounds are isotypic, and some are polymorphic. However, many polymorphs of ultraphosphates  $\text{LnP}_5\text{O}_{14}$  have not been realised to date. Herein, we present the synthesis and crystal structure of an orthorhombic polymorph of  $\text{CeP}_5\text{O}_{14}$ .

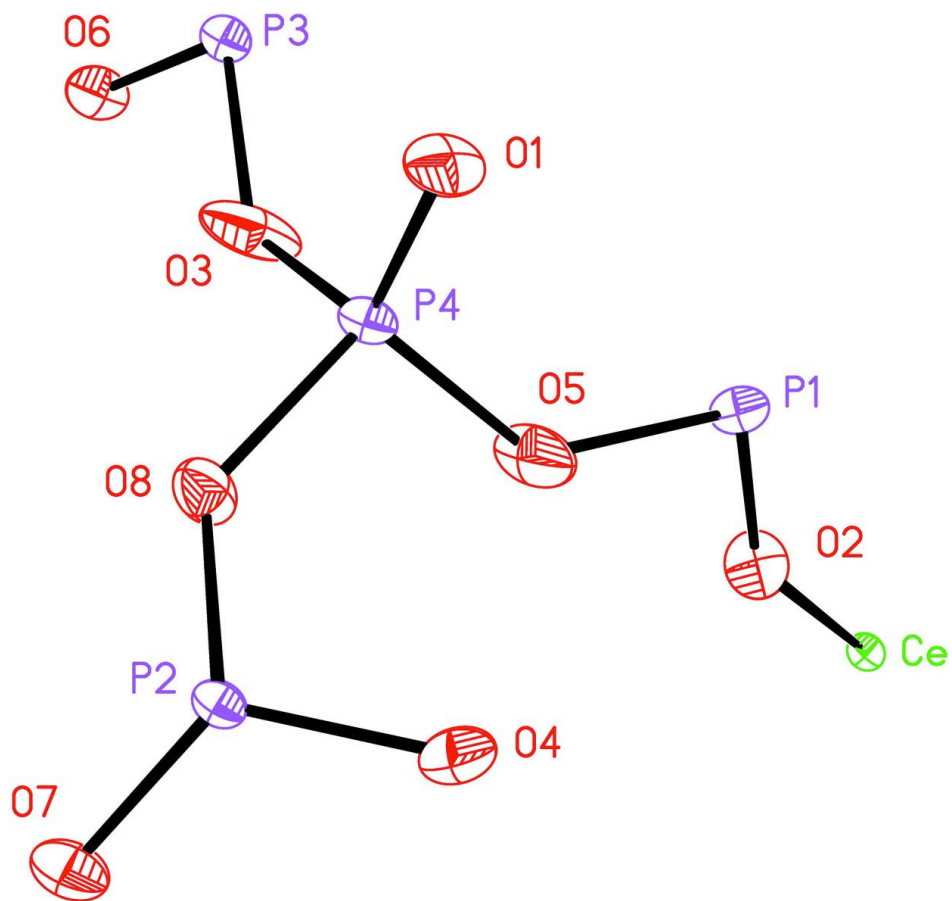
In the structure (Figs. 1 and 2), the  $\text{Ce}^{3+}$  cation plays an important bridging role, connecting neighbouring  $(\text{P}_5\text{O}_{14})^{3-}$  anionic ribbons. The  $\text{CeO}_8$  polyhedron is corner-sharing with eight  $\text{PO}_4$  tetrahedra, with the Ce—O bond distances ranging from 2.436 (5) to 2.534 (8) Å. The shortest Ce—Ce distance is 5.2271 (9) Å. The  $(\text{P}_5\text{O}_{14})^{3-}$  anionic ribbon may be described as two  $\text{PO}_4$  infinite chains linked by  $\text{P}(2)\text{O}_4$  tetrahedra, as shown in Fig. 3.  $\text{P}(1)\text{O}_4$ ,  $\text{P}(3)\text{O}_4$ , and  $\text{P}(4)\text{O}_4$  tetrahedra are corner-shared to form screwed infinite chains along the  $b$  axis.  $\text{P}(2)\text{O}_4$  tetrahedra are corner-shared with two surrounding  $\text{PO}_4$  infinite chains along the  $a$  axis. Thus, a  $(\text{P}_5\text{O}_{14})^{3-}$  anionic ribbon is observed parallel to  $b$ .

### S2. Experimental

The title compound was prepared by a high-temperature solution reaction, using analytical reagent  $\text{CeO}_2$  and  $\text{NH}_4\text{H}_2\text{PO}_4$  in a molar ratio corresponding to  $\text{Ce}/\text{P} = 1:12$ . Starting mixtures were finely ground in an agate mortar to ensure optimal homogeneity and reactivity, then placed in a platinum crucible and heated at 373 K for 4 h. Afterwards, the mixtures were reground and heated to 973 K for 24 h. Finally, the temperature was cooled to 773 K at a rate of 2 K/h and air-quenched to room temperature. A few colourless, block-shaped crystals were obtained from the melt of the mixture.

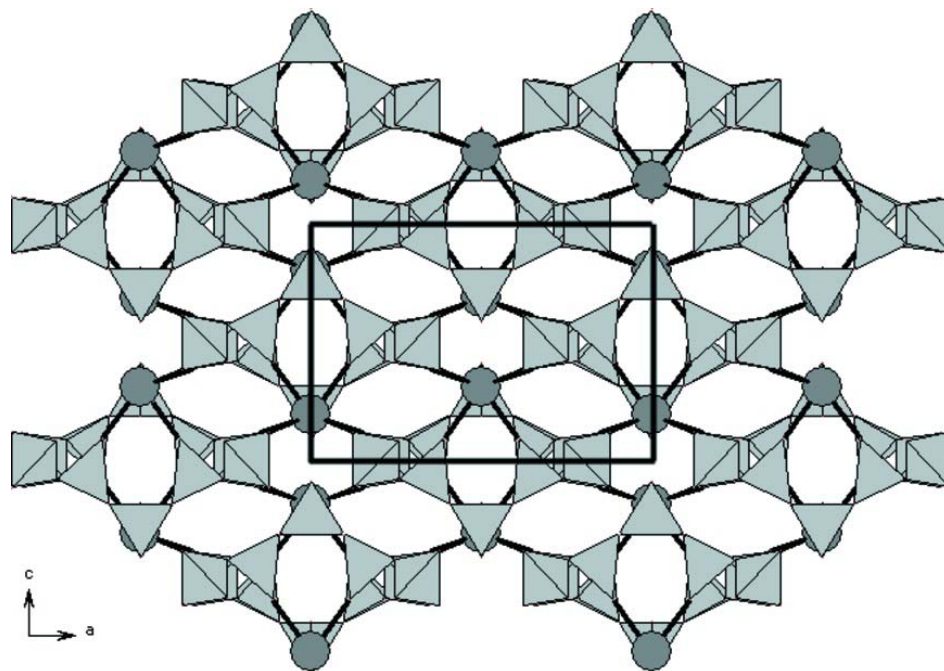
### S3. Refinement

The position of the Ce atom was obtained using direct methods, and the remaining atoms were located in successive difference Fourier syntheses. The chemical composition of the single crystal was confirmed by energy-dispersive X-ray (EDX) analysis, and no impurity elements were detected.

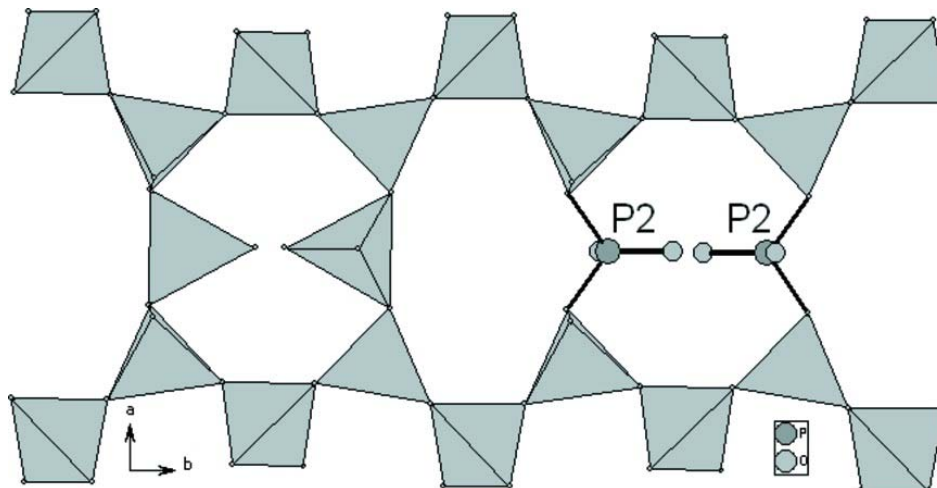


**Figure 1**

Asymmetric unit with displacement ellipsoids shown at 50% probability.

**Figure 2**

Projection of the structure along the  $b$  axis. The tetrahedra represent  $\text{PO}_4$  groups and the gray circles represent  $\text{Ce}^{3+}$  cations.

**Figure 3**

$(\text{P}_5\text{O}_{14})^{3-}$  anionic ribbon running parallel to the  $b$  axis.

### Cerium(III) ultraphosphate

#### Crystal data

$\text{CeP}_5\text{O}_{14}$

$M_r = 518.97$

Orthorhombic,  $Pmna$

Hall symbol:  $-P\ 2ac\ 2$

$a = 13.1252\ (12)\ \text{\AA}$

$b = 8.7991\ (9)\ \text{\AA}$

$c = 9.0741\ (9)\ \text{\AA}$

$V = 1047.97\ (18)\ \text{\AA}^3$

$Z = 4$

$F(000) = 980$

$D_x = 3.289 \text{ Mg m}^{-3}$   
 Mo  $K\alpha$  radiation,  $\lambda = 0.71073 \text{ \AA}$   
 Cell parameters from 2047 reflections  
 $\theta = 2.3\text{--}27.5^\circ$

$\mu = 5.19 \text{ mm}^{-1}$   
 $T = 293 \text{ K}$   
 Block, colourless  
 $0.08 \times 0.08 \times 0.05 \text{ mm}$

*Data collection*

Rigaku Mercury CCD  
 diffractometer  
 Radiation source: fine-focus sealed tube  
 Graphite monochromator  
 $\omega$  scans  
 Absorption correction: multi-scan  
 (*CrystalClear*; Molecular Structure Corporation  
 & Rigaku, 2001)  
 $T_{\min} = 0.663$ ,  $T_{\max} = 0.771$

7608 measured reflections  
 1262 independent reflections  
 1212 reflections with  $I > 2\sigma(I)$   
 $R_{\text{int}} = 0.072$   
 $\theta_{\max} = 27.5^\circ$ ,  $\theta_{\min} = 2.3^\circ$   
 $h = -17 \rightarrow 16$   
 $k = -11 \rightarrow 11$   
 $l = -11 \rightarrow 11$

*Refinement*

Refinement on  $F^2$   
 Least-squares matrix: full  
 $R[F^2 > 2\sigma(F^2)] = 0.048$   
 $wR(F^2) = 0.094$   
 $S = 1.00$   
 1262 reflections  
 99 parameters  
 0 restraints  
 Primary atom site location: structure-invariant  
 direct methods

Secondary atom site location: difference Fourier  
 map  
 $w = 1/[\sigma^2(F_o^2) + 37.6801P]$   
 where  $P = (F_o^2 + 2F_c^2)/3$   
 $(\Delta/\sigma)_{\max} = 0.001$   
 $\Delta\rho_{\max} = 1.70 \text{ e \AA}^{-3}$   
 $\Delta\rho_{\min} = -1.08 \text{ e \AA}^{-3}$   
 Extinction correction: *SHELXL97* (Sheldrick,  
 2008),  $F_c^* = kFc[1 + 0.001x \text{Fc}^2\lambda^3/\sin(2\theta)]^{-1/4}$   
 Extinction coefficient: 0.0114 (15)

*Special details*

**Geometry.** All e.s.d.'s (except the e.s.d. in the dihedral angle between two l.s. planes) are estimated using the full covariance matrix. The cell e.s.d.'s are taken into account individually in the estimation of e.s.d.'s in distances, angles and torsion angles; correlations between e.s.d.'s in cell parameters are only used when they are defined by crystal symmetry. An approximate (isotropic) treatment of cell e.s.d.'s is used for estimating e.s.d.'s involving l.s. planes.

**Refinement.** Refinement of  $F^2$  against ALL reflections. The weighted  $R$ -factor  $wR$  and goodness of fit  $S$  are based on  $F^2$ , conventional  $R$ -factors  $R$  are based on  $F$ , with  $F$  set to zero for negative  $F^2$ . The threshold expression of  $F^2 > \sigma(F^2)$  is used only for calculating  $R$ -factors(gt) *etc.* and is not relevant to the choice of reflections for refinement.  $R$ -factors based on  $F^2$  are statistically about twice as large as those based on  $F$ , and  $R$ -factors based on ALL data will be even larger.

*Fractional atomic coordinates and isotropic or equivalent isotropic displacement parameters ( $\text{\AA}^2$ )*

	$x$	$y$	$z$	$U_{\text{iso}}^*/U_{\text{eq}}$
Ce	0.5000	0.72337 (7)	0.68985 (6)	0.00797 (19)
P1	0.2936 (2)	0.5000	0.5000	0.0113 (6)
P2	0.0000	0.3121 (3)	0.7524 (3)	0.0091 (5)
P3	0.3233 (2)	0.0000	0.5000	0.0102 (5)
P4	0.16332 (14)	0.2351 (2)	0.54996 (19)	0.0098 (4)
O1	0.1129 (4)	0.2256 (7)	0.4081 (6)	0.0189 (12)
O2	0.3474 (4)	0.5859 (7)	0.6151 (6)	0.0182 (12)
O3	0.2451 (5)	0.1123 (8)	0.5815 (6)	0.0295 (16)
O4	0.0000	0.4655 (9)	0.6859 (9)	0.0155 (16)
O5	0.2151 (5)	0.3901 (7)	0.5849 (7)	0.0307 (17)
O6	0.3778 (4)	-0.0799 (6)	0.6175 (6)	0.0165 (12)

O7	0.0000	0.2893 (10)	0.9131 (8)	0.0176 (17)
O8	0.0934 (4)	0.2133 (6)	0.6876 (6)	0.0161 (11)

*Atomic displacement parameters (Å<sup>2</sup>)*

	$U^{11}$	$U^{22}$	$U^{33}$	$U^{12}$	$U^{13}$	$U^{23}$
Ce	0.0074 (3)	0.0090 (3)	0.0075 (3)	0.000	0.000	0.0003 (2)
P1	0.0062 (11)	0.0135 (13)	0.0143 (13)	0.000	0.000	-0.0033 (11)
P2	0.0089 (12)	0.0120 (13)	0.0063 (11)	0.000	0.000	-0.0008 (10)
P3	0.0080 (11)	0.0124 (13)	0.0102 (12)	0.000	0.000	-0.0013 (10)
P4	0.0059 (8)	0.0152 (10)	0.0083 (8)	0.0002 (7)	0.0001 (6)	-0.0019 (7)
O1	0.021 (3)	0.023 (3)	0.013 (2)	0.006 (3)	-0.008 (2)	-0.001 (2)
O2	0.014 (3)	0.023 (3)	0.018 (3)	-0.006 (2)	-0.003 (2)	0.000 (2)
O3	0.029 (3)	0.050 (4)	0.010 (3)	0.028 (3)	0.001 (2)	-0.004 (3)
O4	0.019 (4)	0.012 (4)	0.016 (4)	0.000	0.000	-0.005 (3)
O5	0.034 (4)	0.031 (4)	0.027 (3)	-0.027 (3)	0.019 (3)	-0.015 (3)
O6	0.016 (3)	0.017 (3)	0.016 (3)	0.006 (2)	-0.002 (2)	0.001 (2)
O7	0.021 (4)	0.024 (4)	0.008 (3)	0.000	0.000	-0.002 (3)
O8	0.017 (3)	0.017 (3)	0.014 (2)	0.007 (2)	0.005 (2)	0.004 (2)

*Geometric parameters (Å, °)*

Ce—O2	2.436 (5)	P2—O8 <sup>ix</sup>	1.614 (5)
Ce—O2 <sup>i</sup>	2.436 (5)	P2—O8	1.614 (5)
Ce—O6 <sup>ii</sup>	2.449 (5)	P3—O6 <sup>x</sup>	1.464 (5)
Ce—O6 <sup>iii</sup>	2.449 (5)	P3—O6	1.464 (5)
Ce—O7 <sup>iv</sup>	2.513 (7)	P3—O3 <sup>x</sup>	1.606 (6)
Ce—O1 <sup>v</sup>	2.514 (5)	P3—O3	1.606 (6)
Ce—O1 <sup>vi</sup>	2.514 (5)	P4—O1	1.450 (5)
Ce—O4 <sup>vii</sup>	2.534 (8)	P4—O3	1.549 (6)
P1—O2	1.470 (6)	P4—O5	1.557 (6)
P1—O2 <sup>viii</sup>	1.470 (6)	P4—O8	1.562 (5)
P1—O5 <sup>viii</sup>	1.609 (6)	O1—Ce <sup>iv</sup>	2.514 (5)
P1—O5	1.609 (6)	O4—Ce <sup>xi</sup>	2.534 (7)
P2—O7	1.472 (8)	O6—Ce <sup>xiii</sup>	2.449 (5)
P2—O4	1.479 (8)	O7—Ce <sup>vi</sup>	2.513 (7)
O2—Ce—O2 <sup>i</sup>	110.6 (3)	O2 <sup>viii</sup> —P1—O5 <sup>viii</sup>	106.0 (3)
O2—Ce—O6 <sup>ii</sup>	144.55 (18)	O2—P1—O5	106.0 (3)
O2 <sup>i</sup> —Ce—O6 <sup>ii</sup>	74.82 (19)	O2 <sup>viii</sup> —P1—O5	109.8 (3)
O2—Ce—O6 <sup>iii</sup>	74.82 (19)	O5 <sup>viii</sup> —P1—O5	100.4 (6)
O2 <sup>i</sup> —Ce—O6 <sup>iii</sup>	144.55 (18)	O7—P2—O4	121.9 (5)
O6 <sup>ii</sup> —Ce—O6 <sup>iii</sup>	81.8 (3)	O7—P2—O8 <sup>ix</sup>	106.7 (3)
O2—Ce—O7 <sup>iv</sup>	72.54 (17)	O4—P2—O8 <sup>ix</sup>	110.1 (3)
O2 <sup>i</sup> —Ce—O7 <sup>iv</sup>	72.54 (17)	O7—P2—O8	106.7 (3)
O6 <sup>ii</sup> —Ce—O7 <sup>iv</sup>	76.3 (2)	O4—P2—O8	110.1 (3)
O6 <sup>iii</sup> —Ce—O7 <sup>iv</sup>	76.3 (2)	O8 <sup>ix</sup> —P2—O8	98.9 (4)
O2—Ce—O1 <sup>v</sup>	142.43 (19)	O6 <sup>x</sup> —P3—O6	121.5 (5)

O2 <sup>i</sup> —Ce—O1 <sup>v</sup>	79.83 (19)	O6 <sup>x</sup> —P3—O3 <sup>x</sup>	105.8 (3)
O6 <sup>ii</sup> —Ce—O1 <sup>v</sup>	72.48 (18)	O6—P3—O3 <sup>x</sup>	110.6 (3)
O6 <sup>iii</sup> —Ce—O1 <sup>v</sup>	118.08 (19)	O6 <sup>x</sup> —P3—O3	110.6 (3)
O7 <sup>iv</sup> —Ce—O1 <sup>v</sup>	142.65 (14)	O6—P3—O3	105.8 (3)
O2—Ce—O1 <sup>vi</sup>	79.83 (19)	O3 <sup>x</sup> —P3—O3	100.5 (5)
O2 <sup>i</sup> —Ce—O1 <sup>vi</sup>	142.43 (19)	O1—P4—O3	116.1 (3)
O6 <sup>ii</sup> —Ce—O1 <sup>vi</sup>	118.08 (19)	O1—P4—O5	115.5 (4)
O6 <sup>iii</sup> —Ce—O1 <sup>vi</sup>	72.48 (18)	O3—P4—O5	105.7 (4)
O7 <sup>iv</sup> —Ce—O1 <sup>vi</sup>	142.65 (14)	O1—P4—O8	115.8 (3)
O1 <sup>v</sup> —Ce—O1 <sup>vi</sup>	72.2 (3)	O3—P4—O8	100.0 (3)
O2—Ce—O4 <sup>vii</sup>	71.29 (16)	O5—P4—O8	101.6 (3)
O2 <sup>i</sup> —Ce—O4 <sup>vii</sup>	71.29 (16)	P4—O1—Ce <sup>iv</sup>	163.4 (4)
O6 <sup>ii</sup> —Ce—O4 <sup>vii</sup>	138.78 (13)	P1—O2—Ce	148.0 (4)
O6 <sup>iii</sup> —Ce—O4 <sup>vii</sup>	138.78 (14)	P4—O3—P3	141.9 (4)
O7 <sup>iv</sup> —Ce—O4 <sup>vii</sup>	113.9 (3)	P2—O4—Ce <sup>xi</sup>	129.5 (5)
O1 <sup>v</sup> —Ce—O4 <sup>vii</sup>	79.0 (2)	P4—O5—P1	135.1 (4)
O1 <sup>vi</sup> —Ce—O4 <sup>vii</sup>	79.0 (2)	P3—O6—Ce <sup>xii</sup>	148.7 (3)
O2—P1—O2 <sup>viii</sup>	122.6 (5)	P2—O7—Ce <sup>vi</sup>	174.7 (6)
O2—P1—O5 <sup>viii</sup>	109.8 (3)	P4—O8—P2	132.2 (4)

Symmetry codes: (i)  $-x+1, y, z$ ; (ii)  $-x+1, y+1, z$ ; (iii)  $x, y+1, z$ ; (iv)  $-x+1/2, -y+1, z-1/2$ ; (v)  $x+1/2, -y+1, z+1/2$ ; (vi)  $-x+1/2, -y+1, z+1/2$ ; (vii)  $x+1/2, y, -z+3/2$ ; (viii)  $x, -y+1, -z+1$ ; (ix)  $-x, y, z$ ; (x)  $x, -y, -z+1$ ; (xi)  $x-1/2, y, -z+3/2$ ; (xii)  $x, y-1, z$ .