

Co₅BP₃O₁₄: The First Borophosphate with Planar BO₃ Groups Connected to PO₄ Tetrahedra

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Most of the best known materials with optical and electro-optical applications are either *borates* or *phosphates*. Names such as **BBO** (β -BaB₂O₄),¹ **LBO** (LiB₃O₅),² **KTP** (KTiOPO₄),³ and **KDP** (KH₂PO₄),³ are well-known commercially and are heavily used industrially for making a range of different optical elements. In the last couple of years the first few compounds combining both borate and phosphate groups were synthesized and structurally characterized. High-temperature syntheses have produced handful of metal borophosphates, all of main group metals. These are the following: MBPO₅, where M = Ca or Sr,⁴ M₃BP₃O₁₂, where M = Ba or Pb,^{4,5} and Na₅B₂P₃O₁₃.⁶ The main structural features in all of them is that boron is *tetrahedrally* coordinated by oxygen, and that the BO₄ and PO₄ tetrahedra share corners and build infinite chains. The lower temperature–higher pressure approach (hydrothermal synthesis) has been used by the nature to produce two minerals: Mg₃B₂P₂O₈(OH)₆·6H₂O with dimeric tetrahedral units of BPO₆⁶⁻,⁷ and Mn₃-BPO₄(OH)₆ with isolated BO₄ and PO₄ tetrahedra.⁸ The same method in laboratory conditions has also yielded the first zeolite-like borophosphate, CoB₂P₃O₁₂(OH)·C₂H₁₀N₂, with an infinite framework of corner sharing BO₄- and PO₄-tetrahedra and CoO₆-octahedra.⁹

Here we report on the synthesis and structural characterization of the first transition metal borophosphate with *planar* BO₃ groups that are connected to tetrahedral PO₄ groups. The title compound was made in a flux of B₂O₃ (*ca.* 10-fold excess) from a stoichiometric mixture of CoCO₃·xH₂O (Aldrich) and H₃PO₄ (Aldrich, crystals, 98+%). Heating the mixture at 950 °C for 12 h and then slow cooling it (1°/min) to room temperature provided relatively large (up to 3 mm) crystals with deep blue color and with no particular shape. The crystals were embedded in a light purple glassy matrix of B₂O₃ mixed with most likely cobalt phosphates. They were mechanically separated from the matrix since the latter could not be washed out (completely) and then cut to smaller pieces for structure determination. No other crystalline phase was detected.

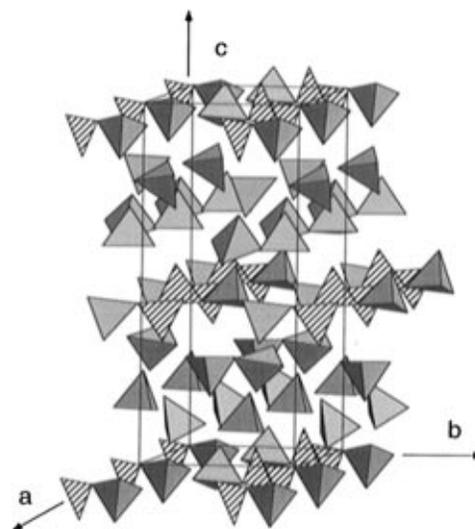


Figure 1. General view of the unit cell of Co₅BP₃O₁₄ with the cobalt atoms omitted for clarity. Planar BO₃ groups (striped triangles) share corners with PO₄ tetrahedra to form BPO₆⁴⁻ dimers. Layers of dimers run parallel to the *a,b* plane and are separated by double layers of isolated PO₄ tetrahedra.

Single-crystal studies¹⁰ revealed a new type of B–O–P dimer in the structure. The dimer, BPO₆⁴⁻, is a triangular BO₃ unit sharing an oxygen atom with a PO₄ tetrahedron (see Synopsis). In addition to the PO₄ tetrahedra in the dimers there are also twice as many isolated ones. There are no oxygen atoms coordinated only to cobalt atom(s); i.e., they are either part of PO₄ or BPO₆ units. Thus the formula can be written as 5Co²⁺ + BPO₆⁴⁻ + 2PO₄³⁻, and the compound should be considered a true phosphate–borophosphate. The dimers form layers perpendicular to the *c*-axis (Figure 1). The plane of the BO₃ groups is nearly perpendicular to the *a*-axis, and the B–P direction of the dimers is nearly along the *b*-axis. The layers of dimers are separated by double “layers” of PO₄ tetrahedra. The B–O–P angle in the dimers, 131.4(5)°, is within the expected range for a two-bonded oxygen atom. Although the BO₃ groups are not equilateral triangles, the angles around B, 125.5(7), 122.3(7), and 112.2(6)°, add up to 360(1)°, indicating that the group is indeed planar. The B–O and P–O separations range from 1.363(9) to 1.401(9) Å for B–O, and from 1.519(5) to 1.572(5) Å for P–O (for all PO₄ tetrahedra), and are well within the normal limits. The longest P–O and B–O distances are the ones to the shared oxygen atom, as expected.¹¹

The IR spectrum of the compound shows strong but broad bands in the 1400–800 cm⁻¹ region. This is consistent with P–O and B–O stretches for PO₄ and BO₃ groups.^{12–14}

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 - (10) The structure was solved by direct methods following data collection on a 0.20 × 0.15 × 0.15 mm single crystal (irregular piece of a larger deep-blue crystal) at 20°C on a CAD4 instrument with monochromated Mo K α radiation ($\lambda = 0.71073$ Å). Crystal data: monoclinic, *P2₁/c* (No. 14), *Z* = 4, *a* = 6.405(1) Å, *b* = 8.238(1) Å, *c* = 18.955(4) Å, $\beta = 96.93(3)^\circ$, *R*(*F*)/*R*_w(*F*²) = 3.8/6.9% for 1388 independent observed reflections (*I* ≥ 2 σ _{*I*}; *R*_{ave} = 3.7%, 1905 total number of reflections; 2 θ ≤ 50°; *h,k,l* ±1 octants collected) and 224 variables, and with absorption ($\mu = 87.6$ cm⁻¹) corrected with the aid of 4 ψ -scans at different θ angles (0.8902 < transmission < 0.9965). All atoms except boron were refined with anisotropic thermal parameters. Application of XABS for absorption correction did not lead to better results and was not used.

- (11) For BO₃ groups connected similarly to BO₄ groups, the corresponding B–O distances for single bonded and shared oxygen atoms are 1.325(6) and 1.414(6) Å, respectively, in CuTmB₅O₁₀ (Schaefer, J.; Bluhm, K. Z. *Naturforsch.* **1995**, *50B*, 762) and 1.33(1) and 1.40(1) Å, respectively, in CuTb₂B₈O₁₆ (Schaefer, J.; Bluhm, K. *ibid.* **1995**, *50B*, 757).
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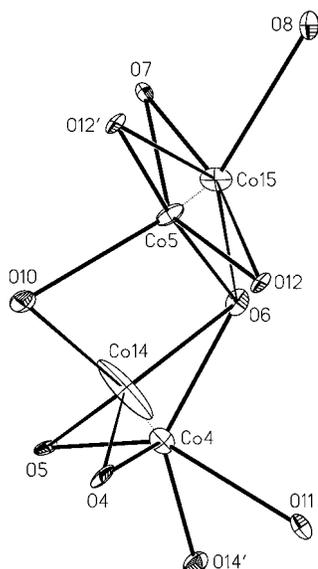


Figure 2. Shown are the two split cobalt positions, the Co4–Co14 and Co5–Co15 pairs (see the text). The atoms of the first pair are 5- and 4-coordinated by oxygen in a distorted trigonal bipyramid and in a face sharing tetrahedron, respectively. The second pair is in an octahedron that is elongated along O8–O10. The two cobalt atoms are thus 5-coordinated in two base-sharing square pyramids.

There are five crystallographically different cobalt atoms in the structure. Two of them, Co1 and Co3, are octahedrally coordinated with Co–O distances ranging from 2.010(5) to 2.187(5) Å. Another cobalt, Co2, is five-coordinated in a triangular bipyramid with distances to oxygen in the range 2.002(5)–2.123(5) Å. The remaining two cobalt atoms occupy two split positions, Co4–Co14 and Co5–Co15 (Figure 2). Initially the occupancies of these 4 sites were refined independently. The results were 90(1) and 10(1)% occupancies for Co4 and Co14, respectively, and 79(1) and 20(1)% occupancies for Co5 and Co15, respectively. Another set of X-ray data was later collected from a second crystal, and the corresponding numbers for these occupancies were 90(1) and 9(1)% for the Co4–Co14 pair, and 77(2) and 23(2)% for the Co5–Co15 pair.¹⁵ This was a clear indication that each pair was fully occupied, and for the final refinement the sums of the occupancies were constrained to 100% for each pair. It can be seen from Figure 2 that Co5 and Co15 occupy the two halves of an octahedron (O6,7,8,10, 2 × O12) elongated along two opposite corners (O8 and O10). The coordination of the two cobalt sites, therefore, is nearly square pyramidal. The Co–O distances range from 1.933(5) to 2.223(5) Å for Co5, and from 2.042(9) to 2.30(2) Å for Co15.

The oxygen coordination around the Co4–Co14 pair is more difficult to describe as one polyhedron. Co4 is 5-coordinate and the corresponding polyhedron could be viewed as a heavily distorted trigonal bipyramid (for the lack of other way of describing it) with O4, O6, and O14 as the base and O5 and

O11 as the opposite apices of the bipyramid (Figure 2). The “distortion” is expressed in moving the two apices away from the Co14 site and toward O14. The distances here range from 2.007(5) to 2.235(5) Å. The other site of this position, Co14, is more or less tetrahedrally coordinated (O4,5,6,10) with one face of the tetrahedron (O4,5,6) shared with the trigonal bipyramid around Co4. Naturally, the distances are shorter in this lower coordination, 1.82–2.34 Å. The tetrahedron is quite irregular, and most likely its distortion is the reason behind the irregular shape of the thermal ellipsoid of the central atom. The irregularity of the tetrahedron is due to the fact that one of its edges, O5–O10, is an edge of a much smaller PO₄ tetrahedron (around P1) at the same time. Thus this edge is much shorter, 2.44 Å, than the other edges, 3.49 Å (average). The result is a rather “flat” tetrahedron around Co14 and a thermal ellipsoid that is elongated perpendicularly to the “plane” of that flat tetrahedron. In addition to this, the two oxygen atoms that are directly in that plane, O6 and O4, are quite closer to Co14, 1.82 and 1.97 Å, respectively, than the other two oxygens, 2.06 and 2.34 Å. This brings the possibility of additional splitting of Co14 above and below the plane. Our attempts to refine the position as such were unsuccessful and proved that this was not the case. Similar results for the thermal ellipsoid of Co14 (elongation along the same direction) were observed from the refinement of the structure from the data taken on the second crystal (see above).

The cobalt polyhedra are quite heavily fused through edges and corners,¹⁶ and form a three-dimensional “network”. Each Co-polyhedron shares three edges and at least one corner with other Co-polyhedra.

Overall the structure of Co₅BP₃O₁₄ could be considered as built of packed but isolated BPO₆⁴⁻ dimers and PO₄ tetrahedra with the Co²⁺ “counteranions” surrounding these units and joining them together. The oxygen atom that is bridging in the BPO₆⁴⁻ dimer is the only one with no cobalt neighbors. The others, except O8 and O10, have two such neighbors and therefore are 3-bonded. O8 and O10 are 4-bonded when the Co15 or Co14 positions, respectively, are occupied (Figure 2).

Apparently dimers such as BPO₆ and PO₄ tetrahedra can not pack well and leave “appropriate” holes for the cobalt atoms at the same time. This may be the explanation for the distorted cobalt polyhedra and also for the split positions. The fact that the structure forms despite the unfavorable Co-coordination suggests that the latter is not the primary driving force but is rather a consequence of the packing. The higher-energy positions, Co14 and Co15, are apparently not that unfavorable at the high temperature of the synthesis. They get partially occupied at these temperatures and can not get completely empty (equilibrated) upon cooling. Lower cooling rates are being tested to check if the compound can form with zero occupancies of these sites. Substitution of larger metals for the two cobalt atoms may also lead to full occupancies of one set of sites and leave the others empty.

The fact that BO₃ can connect to PO₄ is quite encouraging that compounds with infinite three-dimensional networks based on such or similar triangle-to-tetrahedron bonding may be accessible.

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Supporting Information Available: Tables of data collection and refinement details, atomic coordinates and thermal parameters, anisotropic thermal parameters, and complete bond distances and angles and figures showing the fused cobalt polyhedra (8 pages). Ordering information is given on any current masthead page.

(15) The second data set was refined to $R(F) = 4.5\%$. Boron could not be refined with anisotropic thermal parameters.

(16) The Co1-polyhedron shares edges with Co2-, Co3-, and Co4/14-polyhedra, and a corner with a second Co4/14-polyhedron. The Co2-polyhedron shares edges with Co1-, Co3-, and Co4/14-polyhedra, and a corner with a Co5/15-polyhedron. The Co3-polyhedron shares edges with Co1-, Co2-, and Co5/15-polyhedra, and corners with Co4/14- and an additional Co5/15-polyhedra. The Co4/14-polyhedron shares edges with Co1-, Co2-, and Co5/15-polyhedra, and a corner with a Co3-polyhedron. The Co5/15-polyhedron shares edges with Co3-, Co4/14-, and another Co5/15-polyhedra, and corners with Co2- and an additional Co3-polyhedra. Available as Supporting Information are three figures showing the way the cobalt polyhedra are fused.