Nitride Spinel: An Ultraincompressible High-Pressure Form of BeP$_2$N$_4$

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Dedicated to Dr. Klaus Römer on the occasion of his 80th birthday

Abstract: Owing to its outstanding elastic properties, the nitride spinel γ-Si$_3$N$_4$ is of considered interest for materials scientists and chemists. DFT calculations suggest that Si$_3$N$_4$-analog beryllium phosphorus nitride BeP$_2$N$_4$ adopts the spinel structure at elevated pressures as well and shows outstanding elastic properties. Herein, we investigate phenakite-type BeP$_2$N$_4$ by single-crystal synchrotron X-ray diffraction and report the phase transition into the spinel-type phase at 47 GPa and 1800 K in a laser-heated diamond anvil cell. The structure of spinel-type BeP$_2$N$_4$ was refined from pressure-dependent in situ synchrotron powder X-ray diffraction measurements down to ambient pressure, which proves spinel-type BeP$_2$N$_4$ a quenchable and metastable phase at ambient conditions. Its isothermal bulk modulus was determined to 325(8) GPa from equation of state, which indicates that spinel-type BeP$_2$N$_4$ is an ultraincompressible material.

Due to a broad range of materials properties and applications, oxide spinels with the general formula AB$_2$O$_4$ (A, B = metal ions) are an extensively investigated field of research and numerous compounds have been reported. In contrast, only few representatives of nitride spinels (AB$_2$N$_4$) have been prepared, as yet. However, they have already been proven to compete with oxide materials for outstanding materials properties, especially with regard to mechanical resilience.

The synthesis of the group 14 nitrides γ-Si$_3$N$_4$[3,4] and Sn$_3$N$_4$[5] heralded a new era of nitride chemistry, as these compounds represent the first nitride spinels. γ-Si$_3$N$_4$ has been prepared in diamond anvil cells (DAC),[3] multianvil presses,[4] as well as in shockwave experiments,[7] and recently even the preparation of macroscopic transparent polycrystalline γ-Si$_3$N$_4$ windows has been achieved.[6] The isothermal bulk modulus $K_0$ and the Vickers hardness $H_V$ of Si$_3$N$_4$ have been determined to $K_0 = 290–317$ GPa[3,6-10] and $H_V = 30–43$ GPa[8,10-12] which makes it one of the most incompressible and hardest low-density materials.

Due to the topological rigidity of spinels, they are considered to intrinsically feature outstanding elastic properties, which might be further enhanced by strong covalent A–N and B–N bonds in the case of nitride spinels.[13-16] The elemental diversity of nitride spinels, however, is comparatively small, as experimental and theoretical research on nitride spinels has most widely been limited to the binary and ternary nitrides of C, Si, Ge, Sn, Pb, Ti, and Zr[16-19] and only nitride spinels of tetravalent cations (AIV, BIV = Si, Ge, Sn) have been prepared, as yet.[5,6,20]

Besides tetravalent cations, a nitride spinel with the general formula AB$_2$N$_4$ may also be composed of AVI and BIII (AVI$^4$BIII$^3$N$_4$) or AVI and BIV cations (AVI$^4$BIV$^3$N$_4$), when electrostatic neutrality is stipulated. The II–V combination has been reported for several phosphorus(V) nitride materials with the general formula $M^6$P$_4$N$_4$ ($M^6$ = Be, Ca, Sr, Ba, Mn, Cd), which form PN$_4$ tetrahedra based networks.[21-22] To the best of our knowledge, a spinel-type phase, however, has not been reported for any AVI$^4$BIII$^3$N$_4$ or AVI$^4$BIV$^3$N$_4$, as yet.

Theoretical investigations have predicted spinel-type (sp) BeP$_2$N$_4$ as a stable polymorph at elevated pressures, which makes it a promising candidate for the first A$^{3+}$B$^{2+}$N$_4$-type nitride spinel.[23-25] Hitherto, only phenakite-type (phe) BeP$_2$N$_4$ has been reported, which is isoelectronic and homeotypic with β-Si$_3$N$_4$ and features BeN$_4$ and PN$_4$ tetrahedra.[25,26,27] By analogy with the Si$_3$N$_4$ polymorph, phonon BeP$_2$N$_4$ is considered to undergo a phase transition into the regular spinel structure with Be and P occupying tetrahedral and octahedral voids of the cubic close-pack ing of N, respectively.[25] BeN$_4$ tetrahedra are a common motif in crystal chemistry of beryllium nitrides,[24] whereas PN$_4$ octahedra have only been reported in the high-pressure polymorph β-BP$_2$N$_4$, recently.[25]

The phenakite- to spinel-type transition pressure of BeP$_2$N$_4$ has been predicted to 14–24 GPa from DFT calculations and due to its covalent character, sp-BeP$_2$N$_4$[20] is suggested to be quenchable to ambient pressure as a meta-
stable phase.[21,23,24] Its isothermal bulk modulus has been calculated to be in the range of 263–291 GPa, which emphasizes the kinship with γ-Si₃N₄.[21,23–25] Moreover, the Vickers hardness \( H_V \) of sp-BeP₂N₄ has been estimated to approximately \( H_V = 45 \) GPa using (semi-)empirical approaches, which would make it a promising candidate for a superhard low-density material.[24,31]

Herein, we report on the phe-BeP₂N₄–sp-BeP₂N₄ phase transition at 47 GPa, which was investigated in a laser-heated DAC employing in situ synchrotron X-ray diffraction (XRD) measurements. The structure of sp-BeP₂N₄ was refined using the Rietveld method and its elastic properties have been investigated upon cold decompression to ambient pressure.

phe-BeP₂N₄ was initially synthesized from Be₃N₂ and P₃N₅ in a large volume press at 7 GPa and 1500°C, employing the multianvil technique [Eq. (1), more details are provided in the Supporting Information].[21]

\[
\text{BeN}_2 + 2 \text{P}_2 \text{N}_3 \rightarrow 3 \text{phe-BeP}_2 \text{N}_4
\]

To select a suitable particle for in situ high-pressure investigations and to verify the phenakite-type structure of BeP₂N₄, several polycrystalline grains were screened by synchrotron XRD measurements at ambient conditions (Supporting Information, Figure S2). Integration of the most intense domain of a multi-domain crystalline grain yielded a suitable single-crystal data set (Figure S3), from which the structure of sp-BeP₂N₄ was elucidated (R3 \( \bar{n} \) no. 148), \( a = 12.6979(15) \) Å, \( c = 8.3595(10) \) Å, \( V = 1167.3(5) \) Å³, \( Z = 18 \). All atoms were refined with anisotropic displacement parameters and the mean interatomic Be–N and P–N distances are 1.734(15) and 1.636(8) Å, respectively, which is in line with values that have been reported for the binary nitrides.[26,32] The here obtained structural model verifies the model previously reported by Pucher et al. that has been solved and refined from powder XRD data (Tables S4 and S7).[21,33] Figure 1 illustrates the single-crystal structure of phe-BeP₂N₄ as well as the constituting BeN₄ and PN₄ tetrahedra. More detailed information on the synchrotron XRD measurement and the structure refinement of phe-BeP₂N₄ is provided in the Supporting Information (Tables S4–S7).

To investigate the predicted phe-BeP₂N₄–sp-BeP₂N₄ phase transition, the pre-selected particle of phe-BeP₂N₄ was loaded in a DAC with Ne serving as a pressure transmitting medium and ruby as an internal pressure standard. The sample was cold-compressed in two steps to a maximum pressure of 47.3(9) GPa. At both steps a XRD step scan was collected that could be indexed with the metrics of phe-BeP₂N₄ (Figure S8, Table S9). Owing to very low intensities, a refinement of the integrated data, however, was not feasible at those pressures. At 47.3(9) GPa the unit cell of phe-BeP₂N₄ has contracted by approximately 16 vol% in comparison to the ambient pressure model (Figure S11).

To induce the phase transition into the spinel-type structure, the phe-BeP₂N₄ particle was laser-heated from both sides to an average temperature of 1800(200) K at 47.3(9) GPa (NIR fiber laser \( \lambda = 1070 \) nm). This pressure was deemed sufficient for the formation of PN₆ octahedras, as this motif was recently proven at 42 GPa in β-BP₃N₆.[29] The sample was monitored with in situ synchrotron XRD scans for the course of the heating period. After a few seconds, unidentified Bragg reflections appeared and heating for another minute led to an almost full conversion of phe-BeP₂N₄ (Figure 2 and S10). Subsequently, the sample was allowed to cool down to ambient temperature, after which a XRD wide scan was collected. The powder XRD pattern of the new phase matched the Bragg reflections of the predicted spinel-type phase (Figures 2 and S10).[21] Therefore, the experimental pressure of about 47 GPa is proven sufficiently high for the phe-BeP₂N₄–sp-BeP₂N₄ phase transition, but the minimum transition pressure may be most likely significantly lower, considering theoretical investigations on sp-BeP₂N₄ (\( \rho_{\text{trans}} = 14–24 \) GPa)[21,24] and experimental examinations of isoelectronic γ-Si₃N₄ (\( \rho_{\text{trans}} \approx 13 \) GPa).[3,4,9]

Single-crystal XRD measurements of sp-BeP₂N₄ were not feasible, as the title compound did not form any adequate domains (Figure 2a). Therefore, the sp-BeP₂N₄ structure was refined on PXRD data obtained at 47.3(9) GPa employing the Rietveld method (Table S12).[34] The DFT-based model was used as a starting point for the refinement and was subsequently corroborated by the experimental data.[21] sp-BeP₂N₄ crystallizes in the regular spinel structure (Fd\( \bar{3}m \) no. 227, \( a = 7.1948(2) \) Å, \( V = 372.44(3) \) Å³, \( Z = 8 \)) with site symmetries Be(8b, 43m), P(16c, 3m), and N(32e, 5m).[21,32] More detailed information on the structure refinement is provided in the Supporting Information (Tables S12 and S14–S16, Figure S13). No experimental evidence for Be/P disorder or an inverse spinel structure was observed. This is in agreement with the calculations presented by Pucher et al. that characterized the inverse spinel-type BeP₂N₄ to be unfavored towards phe- and sp-BeP₂N₄.[21] The refined crystal structure of sp-BeP₂N₄ and the respective coordination polyhedra of Be and P are illustrated in Figure 3. The interatomic Be–N and
P–N distances at 47.3(9) GPa are 1.635(2) and 1.755(2) Å, respectively, corresponding to fourfold coordinated Be and sixfold coordinated P.

To verify the sp-BeP2N4 structure in terms of electrostatics, the Madelung part of lattice energy (MAPLE) was analyzed. The calculated MAPLE value of sp-BeP2N4 is 58140 kJ mol⁻¹, which is in very good agreement with the values calculated for phe-BeP2N4 (58542 kJ mol⁻¹, ΔE = 0.7%) and the weighted sum of the binary nitrides P3N5 and Be3N2 (58992 kJ mol⁻¹, ΔE = 1.4%). More detailed information on MAPLE calculations are provided in Table S19.

Incremental cold decompression of sp-BeP2N4 to ambient pressure was monitored by in situ PXRD measurements at 17 pressure points (Figure S11, Table S16). The pressure-dependent Rietveld refinements show that sp-BeP2N4 is quenchable to ambient conditions. The expansion of the unit cell upon decompression from 47.3(9) GPa to ambient pressure was 14 vol%, while the interatomic Be–N and P–N distances at ambient pressure expanded to 1.752(2) and 1.808(2) Å, respectively (Table S16, Figure S17). These values are in good agreement with values from the DFT model and with those reported for BeN4 and PN6 polyhedra in Be3N2 and β-BP3N6.

According to DFT calculations, sp-BeP2N4 is considered to show a very low compressibility (263 < K0 < 291 GPa). Thus, the pressure-volume data from pressure-dependent Rietveld refinements were fitted with both, a 2nd and a 3rd order Birch-Murnaghan (BM) equation of state (EoS), yielding the fitting parameters V0 = 423.76(7) Å³, K0 = 305(5) GPa, K0' = 4 (fixed) and V0 = 423.68(6) Å³, K0 = 325(8) GPa, K0' = 2.4(5), respectively (Figure 4, S20). These findings render sp-BeP2N4 an ultracompressible material exceeding the bulk modulus of γ-Si3N4 as well as the predicted values from DFT calculations. Its hardness and thermal stability, however, have not been investigated experimentally, as yet. As the title compound is quenchable to ambient conditions and may form at significantly lower pressures, its synthesis may be reproduced in large volume presses, providing sample amounts suitable for future investigations in terms of its elastic, physical, and optical properties. More detailed information on the BM EoS fits and the elastic properties of sp-BeP2N4 is provided in the Supporting Information.

**Figure 2.** (a) XRD scans of the BeP2N4 sample before (left) and after laser heating at 47.3(9) GPa (right), corresponding to phe- and sp-BeP2N4, respectively. (b) Rietveld refinement of sp-BeP2N4 and Ne at 47.3 (9) GPa from in situ X-ray measurements using synchrotron radiation (λ = 0.2894 Å). Observed and calculated XRD intensities: black circles, gray line; difference plot: dotted gray line; positions of Bragg reflections of sp-BeP2N4 and Ne: black and gray vertical bars. Reflections of minor residues of phe-BeP2N4 are marked by asterisks and weak scattering of the Re gasket is labelled.

**Figure 3.** The crystal structure of sp-BeP2N4 as refined from PXRD data collected at 47.3(9) GPa. Be (gray) occupies tetrahedral and P (black) octahedral voids in a cubic close-packing of N (white), corresponding to the regular spinel structure.

**Figure 4.** The pressure-volume data from pressure-dependent Rietveld refinements were fitted with a 2nd and 3rd order Birch-Murnaghan equation of state (BM EoS), with fitting parameters provided in the main text. The isothermal bulk modulus of >300 GPa renders sp-BeP2N4 an ultracompressible material.
Recapitulating, phe-BeP₂N₄ was synthesized in a high-pressure high-temperature reaction and the literature-known structure model was confirmed by single-crystal synchrotron XRD measurements. As predicted from theoretical studies, phe-BeP₂N₄ was transformed into the spinel-type phase at 47 GPa and 1800 K using a laser-heated DAC. sp-BeP₂N₄ was proven to be quenchable to ambient pressure and it is rendered an ultra compressible material from equation of states. Therefore, the title compound is the first Al⁺⁺B⁺⁺⁻⁻ nitride spinel and a pioneer compound that extends the still narrow field of nitride spinels by introducing ions with oxidation states +II and +V. This should encourage further experimental investigations on mixed nitride spinels, as they appear as promising compounds for next-generation materials. Thus, future investigations may deal with the incorporation of divalent (e.g. Mg, Zn, Cu, Ni) and pentavalent cations (e.g. V, Nb, or Ta) into II-V nitride spinels, which might introduce intriguing optical and magnetic properties to this emerging field of research.

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Conflict of interest

The authors declare no conflict of interest.

Keywords: high-pressure chemistry · nitrides · solid-state structures · spinel · synchrotron radiation

[1] Q. Zhao, Z. Yan, C. Chen, J. Chem. Rev. 2017, 117, 10121, and references therein.
[2] W. Schnick, Angew. Chem. Int. Ed. 1999, 38, 3309; Angew. Chem. 1999, 111, 3511.
[3] A. Zerr, R. Riedel, G. Miehe, G. Schwarz, E. Kroke, H. Fueß, R. Boehrer, Nature 1999, 400, 340.
[4] M. Schwarz, G. Miehe, A. Zerr, E. Kroke, B. T. Poe, H. Fueß, R. Riedel, Adv. Mater. 2000, 12, 885.
[5] a) G. Serghiou, G. Miehe, O. Tschauener, A. Zerr, R. Boehrer, J. Chem. Phys. 1999, 111, 4659; b) K. Leinenweber, M. O’Keeffe, M. Somayazulu, H. Hubert, P. F. McMullan, G. H. Wolf, Chem. Eur. J. 1999, 5, 3076.
[6] N. Scotti, W. Kockelmann, J. Senker, S. Traßel, H. Jacobs, Z. Anorg. Allg. Chem. 1999, 625, 1435.
[7] T. Sekine, H. He, T. Kobayashi, M. Zhang, F. Xu, Appl. Phys. Lett. 2000, 76, 3706.
[8] N. Nishiyama, R. Ishikawa, H. Ohfuji, H. Marquardt, A. Kunoosov, T. Taniguchi, B.-N. Kim, H. Yoshida, A. Masuno, J. Bednarek, et al., Sci. Rep. 2017, 7, 44755.
[9] N. Nishiyama, J. Langer, T. Sakai, Y. Kojima, A. Holzheid, N. A. Gaida, E. Kulik, N. Hirao, S. I. Kawaguchi, T. Iriuone, et al., J. Am. Chem. Soc. 2019, 141, 21915.
[10] A. Zerr, M. Kempt, M. Schwarz, E. Kroke, M. Góken, R. Riedel, J. Am. Chem. Soc. 2002, 85, 86.
[11] J. Z. Jiang, F. Kragh, D. J. Frost, K. Stähler, H. Lindelov, J. Phys. Condens. Matter 2001, 13, L515.
[12] I. Tanaka, F. Oba, T. Sekine, E. Ito, A. Kubo, K. Tatsumi, H. Adachi, T. Yamamoto, J. Mater. Res. 2002, 17, 731.
[13] M. T. Yeung, R. Mohammadi, R. B. Kaner, Annu. Rev. Mater. Res. 2016, 40, 465.
[14] R. Marchand, F. Tessler, A. Le Sauze, N. Dint, Int. J. Inorg. Mater. 2001, 3, 1143.
[15] J. Haines, J. M. Léger, G. Bocquillon, Annu. Rev. Mater. Res. 2001, 31, 1.
[16] T. D. Boyko, A. Moewes, J. Ceram. Soc. Jpn. 2016, 124, 1063.
[17] W. Y. Ching, S.-D. Mo, I. Tanaka, M. Yoshiya, Phys. Rev. B 2001, 63, 64102.
[18] W. Y. Ching, S.-D. Mo, L. Ouyang, I. Tanaka, M. Yoshiya, Phys. Rev. B 2000, 61, 10609.
[19] J. Dong, J. Deslippe, O. F. Sankey, E. Soignard, P. F. McMullan, Phys. Rev. B 2003, 67, 340.
[20] E. Soignard, P. F. McMullan, K. Leinenweber, Chem. Mater. 2004, 16, 5344.
[21] F. J. Pucher, S. R. Römer, F. W. Karaw, W. Schnick, Chem. Eur. J. 2010, 16, 7208.
[22] a) F. W. Karaw, L. Seyfarth, O. Oeckler, J. Senker, K. Landskron, W. Schnick, Chem. Eur. J. 2007, 13, 6841; b) F. W. Karaw, W. Schnick, J. Solid State Chem. 2005, 178, 135; c) F. J. Pucher, A. Marchuk, P. J. Schmidt, D. Wiechert, W. Schnick, Chem. Eur. J. 2015, 21, 6443; d) F. J. Pucher, F. W. Karaw, J. Schnedt on der Gönne, W. Schnick, Eur. J. Inorg. Chem. 2016, 1497.
[23] W. Y. Ching, S. Aryal, P. Rulis, W. Schnick, Phys. Rev. B 2011, 83, 155109.
[24] Y.-C. Ding, B. Xiao, Acta Phys. Chim. Sin. 2011, 27, 1621.
[25] M. Zhang, H. Yan, Y. Zhao, Q. Wei, Comput. Mater. Sci. 2013, 84, 457.
[26] W. L. Bragg, Proc. R. Soc. London Ser. A 1927, 113, 642.
[27] D. Hardie, K. H. Jack, Nature 1957, 180, 332.
[28] a) M. v. Stackelberg, R. Paulus, Z. Phys. Chem. Abt. B 1933, 22, 305; b) P. Eckerlin, A. Rabenau, Z. Anorg. Allg. Chem. 1960, 304, 218.
[29] S. Vogel, M. Bykov, E. Bykova, S. Wendl, S. D. Kłos, A. Pakhomova, S. Chariton, E. Koemets, N. Dubrovinskaia, L. Dubrovinsky, et al., Angew. Chem. Int. Ed. 2019, 58, 9060; Angew. Chem. 2019, 131, 9158.
[30] Within this contribution the spinel-type phase of BeP₂N₄ is denoted as sp-BeP₂N₄ rather than γ-BeP₂N₄, which was used in some pervious references to emphasize the structural relation to γ-Si₃N₄. A β-BeP₂N₄, however, has not been reported, as yet.
[31] a) C.-M. Sung, M. Sung, Mater. Chem. Phys. 1996, 43, 1; b) F. Gao, Phys. Rev. B Condens. Matter Mater. Phys. 2006, 73, 22.
[32] S. Horstmann, E. Irnan, W. Schnick, Angew. Chem. Int. Ed. Engl. 1997, 36, 1873; Angew. Chem. 1997, 109, 1938.
[33] Crystal data of phe-BeP₂N₄ from single-crystal XRD refinement at ambient pressure: M = 126.99 gmol⁻¹, hexagonal, R3 (no. 148), a = 12.6979(15) Å, c = 8.3595(10) Å, V = 1167.3(5) Å³, Z = 18, ρ = 3.252 gcm⁻³, µ = 0.144 cm⁻¹, synchrotron radiation (λ = 0.28940 Å, DESY, PETRAIII, P02.2), T = 293 K, 2825 observed reflections, 1241 independent reflections, 64 parameters, R = 0.0656, wR = 0.0763, R = 0.0763, χ² = 0.1403, GoF = 1.015, residual electron density 1.145, -1.078 Å⁻³. CSD-1946335 contains the supplementary crystallographic data.
for this compound. These data can be obtained free of charge from The Cambridge Crystallographic Data Centre.

[34] H. M. Rietveld, J. Appl. Crystallogr. 1969, 2, 65.

[35] Detailed information on the crystallographic data of sp-BeP\textsubscript{2}N\textsubscript{4} from pressure-dependent Rietveld refinements is provided in the Supporting Information. CSD-1946347 (47.3 GPa), 1946344 (44.6 GPa), 1946343 (40.9 GPa), 1946342 (38.5 GPa), 1946340 (37.7 GPa), 1946339 (34.0 GPa), 1946338 (31.0 GPa), 1946337 (28.5 GPa), 1946336 (21.8 GPa), 1946335 (17.8 GPa), 1946334 (12.6 GPa), 1946346 (11.9 GPa), 1946349 (7.4 GPa), 1946341 (5.0 GPa), 1946348 (3.3 GPa), 1946352 (1.8 GPa), and 1946345 (1 atm) contain the supplementary crystallographic data for this compound. These data can be obtained free of charge from The Cambridge Crystallographic Data Centre.

[36] R. Hoppe, S. Voigt, H. Glaum, J. Kissel, H. P. Müller, K. Bernet, J. Less-Common Met. 1989, 156, 105.

[37] a) F. D. Murnaghan, Proc. Natl. Acad. Sci. USA 1944, 30, 244; b) F. Birch, Phys. Rev. 1947, 71, 809.

[38] The ultraincompressible character, however, does not imply an intrinsic superhard behavior of sp-BeP\textsubscript{2}N\textsubscript{4}, as the hardness of a certain material correlates with its shear modulus rather than with its compressibility (bulk modulus).\cite{13, 15, 16, 25}
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phenakite-type BeP₂N₄ was transformed
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BeP₂N₄ an ultraincompressible material.