

RESEARCH ARTICLE

10.1029/2020JB020660

Spin Transitions and Compressibility of ϵ -Fe₇N₃ and γ' -Fe₄N: Implications for Iron Alloys in Terrestrial Planet Cores

Key Points:

- Spin transition in ϵ -Fe₇N₃ and γ' -Fe₄N at 300 K completes at 43 and 34 GPa, respectively
- The completion of spin transition leads to stiffening in bulk modulus of ϵ -Fe₇N₃, but not in γ' -Fe₄N
- Evidence for spin transitions in Fe-light-element alloys and their effects are reexamined

Supporting Information:

- Supporting Information S1

Correspondence to:

M. Lv, J. Liu and S. M. Dorfman,
lyumingd@msu.edu;
jiacliu@pku.edu.cn;
dorfman3@msu.edu

Citation:

Lv, M., Liu, J., Zhu, F., Li, J., Zhang, D., Xiao, Y., & Dorfman, S. M. (2020). Spin transitions and compressibility of ϵ -Fe₇N₃ and γ' -Fe₄N: Implications for iron alloys in terrestrial planet cores. *Journal of Geophysical Research: Solid Earth*, 124, e2020JB020660. <https://doi.org/10.1029/2020JB020660>

Received 24 JUL 2020

Accepted 17 OCT 2020

Accepted article online 24 OCT 2020

Mingda Lv¹ , Jiachao Liu^{1,2}, Feng Zhu^{3,4} , Jie Li³ , Dongzhou Zhang^{4,5} , Yuming Xiao⁶, and Susannah M. Dorfman¹ 

¹Department of Earth and Environmental Sciences, Michigan State University, East Lansing, MI, USA, ²Now at Key Laboratory of Orogenic Belts and Crustal Evolution, School of Earth and Space Sciences, Peking University, Beijing, China, ³Department of Earth and Environmental Sciences, University of Michigan, Ann Arbor, MI, USA, ⁴Hawaii Institute of Geophysics and Planetology, University of Hawaii at Manoa, Honolulu, HI, USA, ⁵GeoSoiEnviroCARS, University of Chicago, Chicago, IL, USA, ⁶High Pressure Collaborative Access Team (HPCAT), X-ray Science Division, Argonne National Laboratory, Argonne, IL, USA

Abstract Iron nitrides are possible constituents of the cores of Earth and other terrestrial planets. Pressure-induced magnetic changes in iron nitrides and effects on compressibility remain poorly understood. Here we report synchrotron X-ray emission spectroscopy (XES) and X-ray diffraction (XRD) results for ϵ -Fe₇N₃ and γ' -Fe₄N up to 60 GPa at 300 K. The XES spectra reveal completion of high- to low-spin transition in ϵ -Fe₇N₃ and γ' -Fe₄N at 43 and 34 GPa, respectively. The completion of the spin transition induces stiffening in bulk modulus of ϵ -Fe₇N₃ by 22% at ~40 GPa, but has no resolvable effect on the compression behavior of γ' -Fe₄N. Fitting pressure-volume data to the Birch-Murnaghan equation of state yields $V_0 = 83.29 \pm 0.03$ (Å³), $K_0 = 232 \pm 9$ GPa, $K_0' = 4.1 \pm 0.5$ for nonmagnetic ϵ -Fe₇N₃ above the spin transition completion pressure, and $V_0 = 54.82 \pm 0.02$ (Å³), $K_0 = 152 \pm 2$ GPa, $K_0' = 4.0 \pm 0.1$ for γ' -Fe₄N over the studied pressure range. By reexamining evidence for spin transition and effects on compressibility of other candidate components of terrestrial planet cores, Fe₃S, Fe₃P, Fe₇C₃, and Fe₃C based on previous XES and XRD measurements, we located the completion of high- to low-spin transition at ~67, 38, 50, and 30 GPa at 300 K, respectively. The completion of spin transitions of Fe₃S, Fe₃P, and Fe₃C induces elastic stiffening, whereas that of Fe₇C₃ induces elastic softening. Changes in compressibility at completion of spin transitions in iron-light element alloys may influence the properties of Earth's and planetary cores.

1. Introduction

The Fe-Ni alloy that comprises the Earth's core must also contain light elements based on both geophysical observations (Birch, 1952) and compositions of planetary building blocks (McDonough & Sun, 1995), with potential implications for volatile storage and cycling within our planet. The leading candidate light elements for Earth's core include silicon, oxygen, sulfur, carbon, and hydrogen (Poirier, 1994); in addition to a possible mixture of these, nitrogen has been more recently proposed as a candidate light element in the core (e.g., Kusakabe et al., 2019; Minobe et al., 2015) based on structural stability and physical properties of iron nitrides (β -Fe₇N₃) extrapolated to core conditions. Additional support for the presence of iron nitrides in planetary interiors is provided by observations of iron nitrides in iron meteorites (Rubin & Ma, 2017) and in inclusions in superdeep diamonds, which potentially incorporate material from Earth's core-mantle boundary region (Kaminsky & Wirth, 2017) or locally reduced domains of Earth's mantle (Zedgenizov & Litasov, 2017). The behavior of nitrogen-bearing iron alloys and compounds at conditions relevant to both accretion and the modern core is thus important to evaluate the potential abundance of nitrogen in Earth's interior (e.g., Kusakabe et al., 2019; Litasov et al., 2017; Liu et al., 2019; Minobe et al., 2015). The few constraints on the identities and abundances of core light elements include observed seismological characteristics of Earth's inner and outer core, particularly ~4–7% density deficit of the core relative to properties of Fe-Ni noted since Birch (1952). Available constraints on thermoelasticity of solid iron nitrides from previous studies (e.g., Adler & Williams, 2005; Breton et al., 2019; Kusakabe et al., 2019; Litasov et al., 2017) can be extrapolated for comparison to Earth's core, but extrapolation depends on

stability and electronic/magnetic properties of these materials under high pressure conditions which remain poorly understood.

A wide range of stable iron nitride compounds with varying stoichiometries are stabilized by different conditions (De Waele et al., 2019; Wriedt et al., 1987). Stable iron nitrides at 1 bar include nonstoichiometric $\epsilon\text{-Fe}_3\text{N}_x$ ($0.75 < x < 1.4$) with iron atoms arranged in a hexagonal-close-packed structure, and stoichiometric $\gamma'\text{-Fe}_4\text{N}$ adopting a cubic-close-packed structure (Widenmeyer et al., 2014; Wriedt et al., 1987). Previous studies have identified additional structures in the Fe-N system stabilized by high pressure (e.g., De Waele et al., 2019; Wetzels et al., 2019; Widenmeyer et al., 2014). The $\epsilon\text{-Fe}_7\text{N}_3$ structure (same stoichiometry as $\text{Fe}_3\text{N}_x = 1.3$, space group $P6_322$) remains stable up to 51 GPa and 300 K (Adler & Williams, 2005), and was observed to transform to $\beta\text{-Fe}_7\text{N}_3$ above 41 GPa and ~ 1000 K (Minobe et al., 2015). $\gamma'\text{-Fe}_4\text{N}$ (space group $Pm\bar{3}m$) is predicted to decompose to $\beta\text{-Fe}_7\text{N}_3 + \epsilon\text{-Fe}$ at ~ 56 GPa and 300 K based on thermodynamic analysis (Breton et al., 2019). At high temperatures, $\gamma'\text{-Fe}_4\text{N}$ was observed to transform to $\epsilon\text{-Fe}_4\text{N}$ above 1373 K and 8.5 GPa (Guo et al., 2013), and decompose to $\text{Fe} + \beta\text{-Fe}_7\text{N}_3$ above 41 GPa at ~ 1000 K (Minobe et al., 2015). $\beta\text{-Fe}_7\text{N}_3$ was observed to remain stable up to 3100 K and 135 GPa, and proposed to exist in the Earth's solid inner core (Kusakabe et al., 2019). In addition, a new crystal structure of Fe_7N_3 with space group $C2/m$ was predicted to be stable under Earth's core conditions (Sagatov et al., 2019). However, due to the complex stoichiometries and structural variations in iron nitrides at high pressure and temperature conditions, understanding of high-pressure phase stability in this system remains incomplete.

The effects of incorporating nitrogen in iron alloys and compounds include not only modifying stable crystalline structure, but also the arrangement and bonding style of electrons in d orbitals around iron atoms that control magneto-elastic properties (e.g., Sifkovits et al., 1999; Widenmeyer et al., 2014). Electronic structures of iron nitrides have been investigated by first principles calculations and experimental measurements, which indicate that the chemical bonding in $\epsilon\text{-Fe}_7\text{N}_3$ (e.g., Zhang et al., 2012) and $\gamma\text{-Fe}_4\text{N}$ (e.g., dos Santos & Samudio Pérez, 2016) is a complex mixture of metallic, covalent, and ionic characters. Additionally, iron nitrides undergo pressure-induced magnetic transitions, which may affect thermodynamics and elasticities of Fe-N alloys and compounds at high pressures (e.g., dos Santos & Samudio Pérez, 2016; Ishimatsu et al., 2003; Popov et al., 2015). At 1 bar, the d -orbital electrons in Fe in all known Fe-N compounds adopt a high-spin ferromagnetic arrangement and are remarkable for high saturation of magnetism (which generally decreases with N concentration): the magnetic moment of $\epsilon\text{-Fe}_3\text{N}_x$ ranges from 2.0 to $0.2 \mu_B$ per Fe atom as N concentration increases from $x = 1$ to 1.48 (Leineweber et al., 2001), while the magnetic moment of $\gamma'\text{-Fe}_4\text{N}$ is $2.3 \mu_B$ per Fe atom (Dirba et al., 2015). Only a few high-pressure studies on magnetism of the Fe-N system exist, and the magnetic transition pressures of iron nitrides and their effects on elasticities are largely unknown. Experiments on pressure-induced magnetic transitions of $\epsilon\text{-Fe}_3\text{N}_x$ have not been conducted. $\gamma'\text{-Fe}_4\text{N}$ undergoes a ferromagnetic to paramagnetic transition at 24 GPa and 300 K as resolved by X-ray magnetic circular dichroism (XMCD) measurements (Ishimatsu et al., 2003), while first-principles calculations predicted the magnetic to nonmagnetic transition in $\gamma'\text{-Fe}_4\text{N}$ occurs at 250 GPa (Popov et al., 2015). Systematic experimental constraints on pressure-induced magnetic transitions in both $\epsilon\text{-Fe}_3\text{N}_x$ and $\gamma'\text{-Fe}_4\text{N}$ from ferromagnetic to paramagnetic or nonmagnetic state and the coupling between these electronic arrangements and elasticities and phase stability are necessary for an improved understanding of the physical properties of iron nitrides.

The identification of magneto-elastic coupling behavior in other iron alloy systems such as Fe-C, Fe-S, and Fe-P (recently reviewed by Caracas, 2016) provides additional motivation to test whether the Fe-N system behaves similarly. In the electronically and structurally similar Fe-C system, ferromagnetic (FM) Fe-C compounds undergo transitions first to a paramagnetic (PM) state, and then to a low-spin nonmagnetic (NM) state, and these transitions have been proposed to significantly affect compressibility of Fe-C materials (e.g., Chen et al., 2012, 2018; Lin, Struzhkin, et al., 2004; Mookherjee et al., 2011; Prescher et al., 2012). The pressure-induced magnetic transition of Fe-S (e.g., Chen et al., 2007; Lin, Fei, et al., 2004) and Fe-P compounds (e.g., Gu et al., 2014, 2016; Lai et al., 2020) have also been reported to affect compressibility and sound velocities. Due to the lack of characterization of electronic states at high pressures in previous studies of compression and phase transitions of iron nitrides (e.g., Adler & Williams, 2005; Breton et al., 2019; Litasov et al., 2017), the amount and role of N in Earth's core relative to other candidate light elements remains poorly constrained.

Magnetic transitions at high pressures have been experimentally detected using methods that directly characterize electronic states, as well as methods that indirectly assess magnetism through its effects on elasticity and compression behavior. The total spin moment of Fe, ranging from high to low spin, can be characterized by X-ray emission spectroscopy (XES). The appearance of the satellite emission peak K_{β}' located at the lower energy relative to the main emission peak $K_{\beta 1,3}$ is a result of the $3p$ - $3d$ core-hole exchange interaction in the final state of the emission process. That is, the intensity of the satellite peak depends on the spin polarization of the $3d$ shell and is sensitive to the net magnetic spin state. The collapse of the magnetization of Fe is characterized by the disappearance of the low-energy satellite due to the loss of $3d$ magnetic moment (e.g., Badro et al., 2003, 2004). Therefore, the local spin moment change of iron atoms revealed by XES can distinguish between high-spin (FM or PM) states and low-spin (NM) states. XES spectroscopy performed at high pressures using a synchrotron X-ray source has been used to study magnetic spin transitions in Fe-C, Fe-S, and Fe-P compounds (e.g., Chen et al., 2014, 2018; Gu et al., 2016; Lin, Struzhkin, et al., 2004; Shen et al., 2003). Characterizing magneto-elastic coupling requires complementary information provided by spectroscopic methods such as X-ray emission and structural/elastic methods such as X-ray diffraction (XRD) to confirm magnetic transitions and discontinuous compression behavior operate in tandem (e.g., Chen et al., 2014). However, no such study has been conducted in the Fe-N system.

Here we present a systematic study of magnetic transitions and compressibility of iron-nitrides, ϵ -Fe₇N₃ and γ' -Fe₄N, using synchrotron XES and XRD measurements up to 60 GPa at 300 K. Compression behavior of both compounds is monitored by dense pressure-volume (P - V) data coverage, combined with total spin moment indicated by XES, to determine any effects of magnetic transitions on the incompressibility of iron nitrides. Observed behavior is compared to the effect of magneto-elastic coupling in other Fe alloys studied using the same protocol.

2. Experimental Methods

High purity ϵ -Fe₇N₃ and γ' -Fe₄N powders (99.9%, Kojundo Chemical Lab. Co. Ltd., average grain size ~ 1 μ m) were used as starting materials. XRD for both samples at ambient conditions confirms unit cell volumes in good agreement with previous studies of ϵ -Fe₇N₃ (Adler & Williams, 2005; Kusakabe et al., 2019; Litasov et al., 2017; Minobe et al., 2015) and γ' -Fe₄N (Adler & Williams, 2005; Guo et al., 2013). For the nonstoichiometric ϵ -Fe₇N₃, the ambient volume measured for our sample $V_0 = 86.32(\pm 0.01)$ \AA^3 is consistent with a linear relationship between unit-cell volume and nitrogen content in ϵ -Fe₃N_x, $V = 10.637x + 72.858$ (Litasov et al., 2017) when x is 1.27.

XES of ϵ -Fe₇N₃ and γ' -Fe₄N was measured up to 60 GPa at intervals of ~ 5 GPa. Compression in the diamond anvil cell (DAC) was performed using two pairs of diamond anvils with 200- μ m flat culet. In each DAC, a flake of ϵ -Fe₇N₃ ($\sim 20 \times 20 \times 10$ μm^3) or γ' -Fe₄N ($\sim 15 \times 23 \times 10$ μm^3) sample was loaded in a 100- μ m diameter sample chamber confined by a preindented Be gasket. The sample chamber was drilled in the center of the Be gasket with preindented thickness of ~ 30 μ m using the laser drilling system at HPCAT (Sector 16) at the Advanced Photon Source (APS), Argonne National Laboratory (ANL) (Hrubiak et al., 2015). Silicone oil (Alfa Aesar) served as the pressure-transmitting medium and a 5- μ m ruby ball was loaded into the sample chamber as the pressure standard. Pressures were determined by ruby fluorescence (H. K. Mao et al., 1986) before and after each XES collection, and differed by up to 10% due to relaxation of the sample or cell assembly. The XES measurements were performed at 300 K at beamline 16-ID-D of the APS, ANL. The incident X-ray beam was focused to 5×7 μm^2 full width at half maximum at the sample position. The fluorescence signal was observed through the Be gasket. The incident X-ray energy was 11.3 keV with a bandwidth of ~ 1 eV was used for the experiments. Fe K_{β} emission was selected by silicon analyzer and reflected to a silicon detector with an energy step of about 0.3 eV. Each spectrum was recorded for about 40 min and three spectra were taken to accumulate at least 30,000 counts at the Fe K_{β} main peak at each pressure. All spectra were normalized to area and aligned to the position of the Fe K_{β} main peak (Figure 2). The high-spin reference is the sample spectrum at 1 bar, and low-spin references are the spectrum of FeS₂ at 1 bar collected using the same setup and the sample spectrum at 60 GPa. Intensity difference between the sample and references was integrated over the energy range of the satellite K_{β}' peak (7,030–7,053.0 eV) using the integrated relative difference method (Z. Mao et al., 2014). Uncertainty in total spin moment was determined based on difference in calculations using FeS₂ vs. pressurized sample as low-spin references.

XRD measurements were carried out at 300 K up to 60 GPa with 1–2 GPa steps. The sample flakes of ϵ -Fe₇N₃ ($\sim 20 \times 20 \times 10 \mu\text{m}^3$) and γ' -Fe₄N ($\sim 15 \times 23 \times 10 \mu\text{m}^3$) were loaded side-by-side in the sample chamber of a DAC with a pair of 300- μm -culet diamonds. The sample chamber was drilled in the center of the Re gasket with a preindented thickness of $\sim 30 \mu\text{m}$ using the laser drilling system at HPCAT (Hrubiak et al., 2015). Au powder (>99.95%, Goodfellow) was spread on top of the samples to serve as the pressure calibrant (Fei et al., 2007). Because the Au (111) peak overlapped with that of ϵ -Fe₇N₃ (110) peak, we use the pressure calculated from Au at the position of the γ' -Fe₄N sample to represent the pressure at all sample positions. A flake of pure Fe (>99.997%, Alfa Aesar) with a size of $\sim 25 \times 23 \times 10 \mu\text{m}^3$ was loaded alongside the samples as a secondary reference to monitor the hydrostaticity of stress conditions in the sample chamber (Liu et al., 2016). Ne was loaded into the sample chamber as the pressure-transmitting medium using the COMPRES/GSECARS gas-loading system (Rivers et al., 2008). The uncertainties in pressures were propagated from the standard deviation of the unit-cell volumes of Au and Ne (if applicable). Angle-dispersive XRD measurements were performed at beamline 13-BM-C of the APS, ANL. The incident X-ray beam had a monochromatic wavelength of 0.434 Å and was focused to $\sim 15 \times 15 \mu\text{m}^2$. Two-dimensional XRD images were recorded on a MAR165 CCD detector and the sample-to-detector distance and the tilt angle of the detector relative to the incident X-ray beam were calibrated using 1-bar diffraction of the NIST 660a LaB₆ standard. XRD images of ϵ -Fe₇N₃, γ' -Fe₄N, and Fe were exposed for 60 s. At each pressure, the XRD patterns were integrated using Dioptas software (Prescher & Prakapenka, 2015). For selected pressures (lowest, highest, and one intermediate pressure), crystal structures were confirmed from XRD data using the full spectrum Le Bail fitting technique (Le Bail, 2012) implemented in the EXPGUI/GSAS software package (Toby, 2001).

3. Results

3.1. No Structural Transition of Fe₇N₃ or Fe₄N

XRD patterns for both iron nitrides within the investigated pressure range at 300 K show sharp and intense peaks from the sample, Au, Ne, and Re, and no new diffraction lines nor splitting of lines were observed. The lattice parameters of ϵ -Fe₇N₃ were obtained by fitting diffraction lines (002), (111), and (112), and that of γ' -Fe₄N was fit from diffraction lines (111) and (200) using PDIndexer (Seto et al., 2010). The uncertainty in the lattice parameters corresponds to one standard deviation obtained in fit using multiple XRD peaks. The pressure at each step was calculated from the lattice parameters of Au by fitting the diffraction lines (111) and (200), and from Ne by fitting (111) and (200) peaks at ~ 19 –60 GPa as well (supporting information Table S1-3). The uncertainties of pressures were propagated from uncertainties of unit cell volumes of Au and Ne, and uncertainties of their equation of state parameters (Fei et al., 2007).

Diffraction data of ϵ -Fe₇N₃ were refined using a *P*6₃22 space group (averaged *wRp* = 2.2%, representatives shown in Figures 1a and 1b) up to 60 GPa. Le Bail refinements of the structure of γ' -Fe₄N were performed with the *Pm* $\bar{3}$ *m* space group (averaged *wRp* = 1.8%, representatives shown in Figures 1c and 1d) up to 60 GPa. Note that previous work indicates that ϵ -Fe₇N₃ is metastable above ~ 40 GPa (Minobe et al., 2015), and γ' -Fe₄N is metastable above ~ 56 GPa (Breton et al., 2019). Both samples continue to adopt the initial structures without dissociation or phase transition up to 60 GPa at 300 K, but above 40 GPa we assume that ϵ -Fe₇N₃ is structurally metastable.

3.2. Spin States of ϵ -Fe₇N₃ and γ' -Fe₄N

The net magnetic spin state of 3*d* electrons of Fe in ϵ -Fe₇N₃ and γ' -Fe₄N can be probed by XES spectra of the *K* _{β} fluorescence lines. At ambient conditions, the XES spectra for both iron nitrides are composed of a dominant *K* _{β 1,3} peak and a lower-energy satellite *K* _{β '} peak, as a result of the 3*p* core-hole-3*d* exchange interaction in the final state of the emission process, consistent with iron entirely in the high-spin state (Figures 2a and 2b). The intensity of the satellite peak in the magnetic/high spin state is lower than that of iron oxides such as FeO and Fe₂O₃ (Badro et al., 2002, 2003), but similar to that of pure iron and iron alloys (such as Fe-C, Fe-P, Fe-S alloys). As pressure increases, the integrated *K* _{β '} peak intensity begins to decrease. The observed decrease demonstrates that the onsets of spin transitions in both compounds are nearly immediate upon compression and no higher than 10 GPa in ϵ -Fe₇N₃ and 5 GPa in γ' -Fe₄N. The integrated *K* _{β '} peak of ϵ -Fe₇N₃ and γ' -Fe₄N disappears at 43 and 34 GPa, respectively, with no further change up to 60 GPa

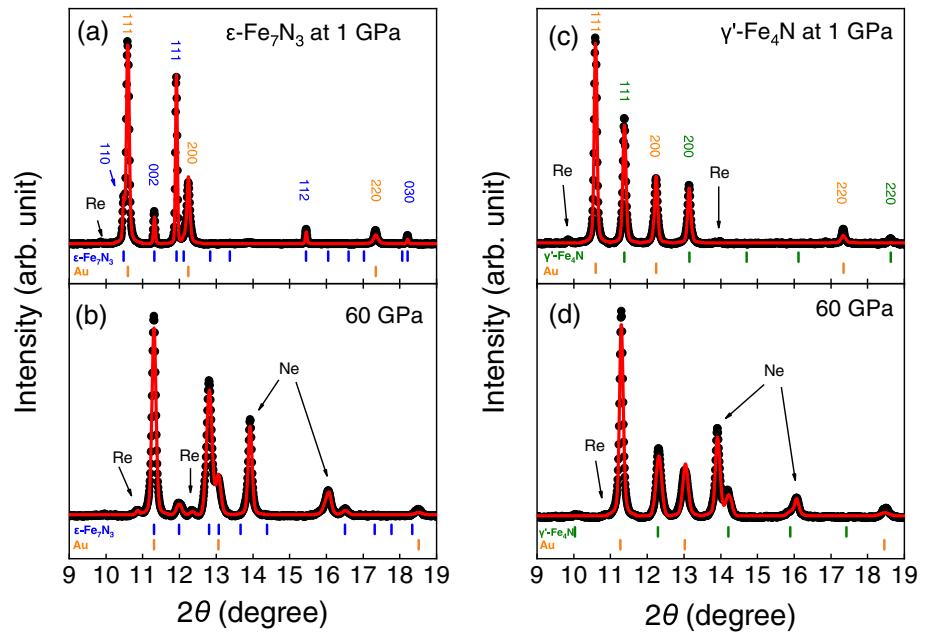


Figure 1. Panels (a) and (b) are representative X-ray diffraction patterns of ϵ - Fe_7N_3 at 1 and 60 GPa at 300 K, respectively; panels (c) and (d) are representative X-ray diffraction patterns of γ' - Fe_4N at 1 and 60 GPa at 300 K, respectively. Le Bail refinements (red solid curves) of observed XRD data (black dots) were carried out after background subtraction, demonstrating all sample peaks match hexagonal ϵ - Fe_7N_3 and cubic γ' - Fe_4N , respectively, within the investigated pressure range. The vertical ticks are ϵ - Fe_7N_3 (blue), γ' - Fe_4N (dark green), and the pressure calibrant, Au (orange). The wavelength of the incident X-ray beam was 0.434 Å.

(Figures 2c and 2d). The decrease of total spin moment of Fe as a function of pressure illustrates both ϵ - Fe_7N_3 and γ' - Fe_4N undergo a gradual spin-pairing transition from high- to low-spin state, with Fe in ϵ - Fe_7N_3 and γ' - Fe_4N fully in low-spin state at pressures higher than 43 and 34 GPa, respectively (Figures 2c and 2d). Spin transition pressures are expected to be upper bounds due to possible effects of pressure hysteresis and nonhydrostatic stress on the spin crossover upon compression (Lin et al., 2013). Observed changes in XES spectra of ϵ - Fe_7N_3 and γ' - Fe_4N correspond to magnetic to nonmagnetic (high to low spin) transitions, but the ferromagnetic to paramagnetic transition, depending on the relative orientations of the individual spins, cannot be detected by XES. However, both ferromagnetic-paramagnetic and magnetic-nonmagnetic transitions may be detected via XRD if they take place and affect compressibility.

3.3. Compression Behavior of ϵ - Fe_7N_3 and γ' - Fe_4N

Pressure-volume (P - V) data obtained from XRD of ϵ - Fe_7N_3 and γ' - Fe_4N at 300 K demonstrate smooth compression without discontinuity in volume (Figures 3a and 4a). Second-order and order-disorder transitions such as magnetic transitions may be continuous in volume but discontinuous in the higher-order derivatives of $P(V)$ (Vocadlo et al., 2002). Subtle effects on the unit cell volume with abrupt changes in incompressibility may be emphasized by the relationship between the Eulerian finite strain ($f_E = [(V_0/V)^{2/3} - 1]/2$) and the normalized stress ($F_E = P/[3f_E(1 + 2f_E)^{5/2}]$) (Angel, 2000) as in previous studies (Chen et al., 2012; Liu et al., 2016). However, it is important to note that the calculation of both F_E and f_E requires priori knowledge of the 1-bar volume (V_0), and using an incorrect value of V_0 produces an anomalous curvature in the f - F plot (Angel, 2000). Thus, to avoid the bias caused by V_0 of the unquenched nonmagnetic phase, we plot the effective strain ($g = [(V_0/V)^{2/3} - 1]/2$), same as f_E , vs. the normalized stress ($G = P/[3(1 + 2g)^{3/2}]$) following the formalism (Jeanloz, 1981) for ϵ - Fe_7N_3 and γ' - Fe_4N (Figures 3b and 4b), respectively.

As is shown in Figure 3b, the g - G plot of ϵ - Fe_7N_3 reveals that the pressure-dependent stress exhibits a linear response to applied strain up to 40 GPa within the established errors. Above 40 GPa, the slope of linearized g - G increases, implying a discontinuity of compression behavior and an increase in the incompressibility given that dG/dg is positively correlated with $(K_0 + P)$. This pressure is within the uncertainty of the completion of the magnetic to nonmagnetic transition (i.e., completion of spin transition) pressure of ~ 40 GPa determined

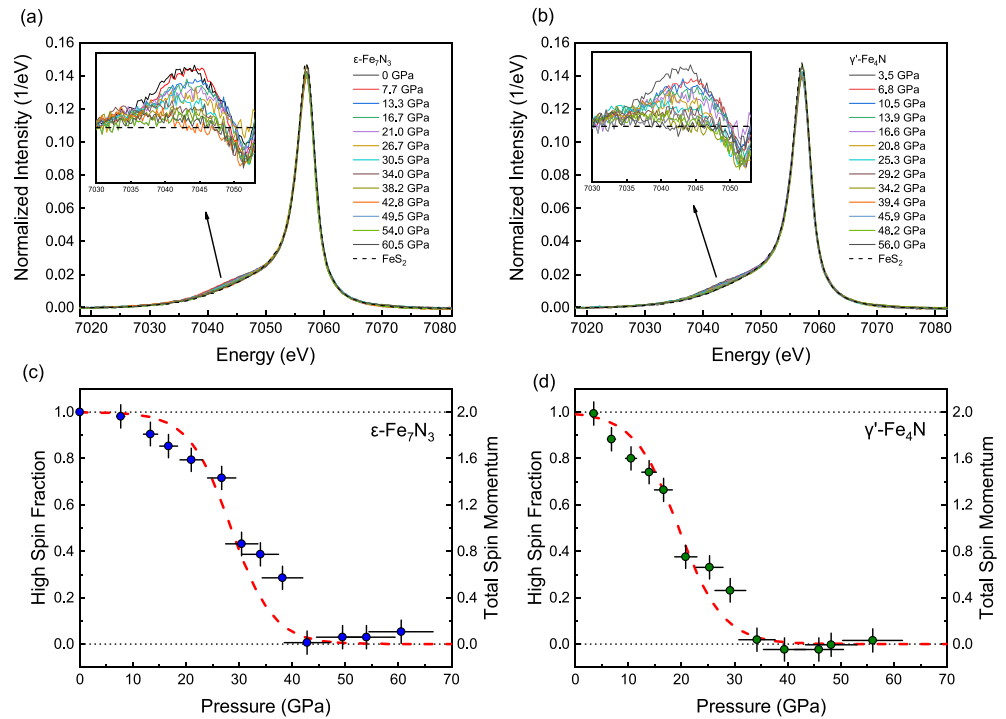


Figure 2. (a–b) Fe- K_{β} fluorescence spectra of ϵ - Fe_7N_3 and γ' - Fe_4N up to 60.5 GPa at 300 K. The XES spectra were normalized to unity in integrated intensity. The top-left inset shows intensity difference of observed satellite emission peak (K_{β}') between 7,030 and 7,053 eV relative to the low-spin reference FeS_2 at 0 GPa (black dashed line). (c–d) High-spin fraction of Fe in ϵ - Fe_7N_3 and γ' - Fe_4N as a function of pressure derived from the XES measurements following integrated relative difference method (Z. Mao et al., 2014). Completion of the spin transition of ϵ - Fe_7N_3 is at ~ 40 GPa, and for γ' - Fe_4N at ~ 30 GPa. The dashed line is fitted by Boltzmann function, and error bars determined by comparing results using FeS_2 vs. sample at 60 GPa as low-spin references. Pressures were determined by ruby fluorescence (H. K. Mao et al., 1986) before and after each XES collection, which differed by up to 10% due to relaxation of the sample or cell assembly.

independently by XES, indicating the elastic stiffening coincides with the magnetic collapse of Fe in ϵ - Fe_7N_3 . In addition, this change of compressibility is similar to the pressure of ϵ - to β - Fe_7N_3 transition (Minobe et al., 2015) observed with laser-heating to promote equilibrium phase transitions. Due to the low pressure of the onset of the spin transition observed by XES, with upper bound ~ 10 GPa, and gradual, broad

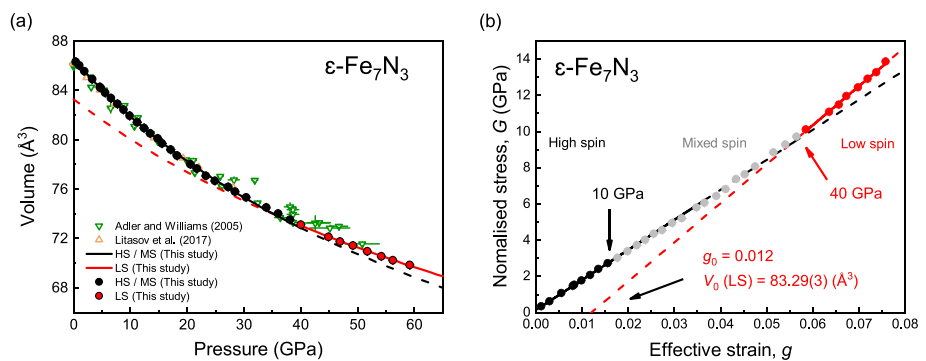


Figure 3. Compression behavior of ϵ - Fe_7N_3 at 300 K. (a) Unit-cell volume of ϵ - Fe_7N_3 up to 60 GPa at 300 K determined from X-ray diffraction measurements in this work (solid circles), together with previous experimental results. The black and red curves represent the third-order Birch-Murnaghan equation of state (BM3-EoS) fits for the data for high-spin (HS) and mixed-spin (MS)/magnetic state (1 bar–40 GPa), low-spin (LS)/nonmagnetic state (40–60 GPa), respectively. (b) Normalized stress G as a function of effective strain g . Solid black, gray, and red circles represent the results of high-spin, mixed-spin, and low-spin state, respectively, as determined by XES. Black and red lines indicate fits of the high-spin and low-spin state $G(g)$ data, respectively. The V_0 for the nonmagnetic state is obtained by extrapolating g to g_0 .

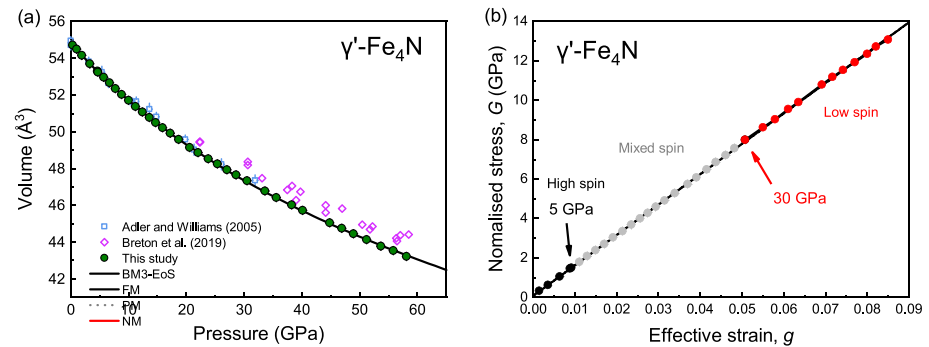


Figure 4. Compression behavior of γ' -Fe₄N at 300 K. (a) Unit-cell volume of γ' -Fe₄N up to 60 GPa at 300 K determined from X-ray diffraction measurements in this work (dark green circles), together with previous experimental results. The black curve represents the third-order Birch-Murnaghan equation of state (BM-EoS) fit of all pressure-volume data from this study. (b) Normalized stress G as a function of effective strain g . Solid black, gray, and red circles represent the results of high-spin, mixed-spin, and low-spin state, respectively, as determined by XES. The black solid line indicates a linear fit for all data. The pressure of onset and completion of spin transition is indicated by XES, but no change in compressibility can be observed in either plot.

pressure range of the transition, it is difficult to resolve a transition from high- to mixed-spin state in the compression behavior. The compression behavior up to 40 GPa may thus represent the mixed-spin state. The crossing point of the g axis (i.e., $G = 0$) and the fitted curve constrain the zero-pressure volume of the nonmagnetic (or low spin state) phase to $83.29 \pm 0.03 \text{ \AA}^3$, with the error propagated from the error of linear fitting and volume at ambient conditions. No stiffening is observed at pressures lower than the spin transition pressure, so no clear evidence is available for any ferromagnetic-paramagnetic transition in ϵ -Fe₇N₃.

In contrast, the calculated G of γ' -Fe₄N can be linearized as a function of g within the investigated pressure range, and no discontinuity is observed (Figure 4b). That is, both onset and completion of spin transition of Fe have little effect on the compression behavior γ' -Fe₄N, and no anomalous compressibility behavior needs to be explained by any other magnetic transition such as a ferromagnetic-paramagnetic transition.

Discontinuities in higher derivatives of compression behavior can also be generated by nonhydrostatic stress in the sample chamber. To rule out this effect on iron nitrides, we consider the pressure gradient observed in Ne medium, microstrain in Au calibrant as determined by peak width, and the behavior of the Fe foil relative to previous measurements under quasi-hydrostatic conditions. The pressure difference determined from the Ne medium at positions of the two iron nitride samples remains less than ~ 0.5 GPa up to the peak pressure of 60 GPa (Table S1-2), consistent with the low strength of Ne. Nonhydrostatic stress generally results in diffraction peak broadening due to microstrain (e.g., Takemura & Dewaele, 2008). We choose the Au (111) peak obtained at the γ' -Fe₄N sample position (Figures 1c and 1d) to examine changes in diffraction peak width as a function of pressure. The normalized FWHM of the Au peak and its trend with pressure are comparable to previous measurements of Au foil and powder in He pressure medium (Takemura & Dewaele, 2008) (Figure S2), indicating hydrostatic conditions up to 17 GPa and quasi-hydrostatic conditions at higher pressures, in agreement with previous characterization of the stress gradient sustained by the pressure medium Ne (Klotz et al., 2009). In addition, compression of both phases of pure Fe remains smooth over the entire pressure range and the condition of the phase transition and compressibility are in agreement with previous studies conducted under quasi-hydrostatic stress (e.g., Dewaele et al., 2006) (Figure S1a). We investigated the P - V data and g - G plot of pure Fe loaded in the same sample chamber as a reference (Figure S1). The discontinuities of both compression curve and g - G plot of Fe at ~ 15 GPa reflect a phase transition of α - to ϵ -Fe, which is in good agreement with previous studies (Dewaele et al., 2006). Therefore, the change in hydrostaticity of Ne at ~ 17 GPa (Figure S2) was not manifested in the compression behavior of the samples, and the change in G - g at ~ 40 GPa of ϵ -Fe₇N₃ is not associated with nonhydrostaticity. Relative to previous studies (Adler & Williams, 2005; Litasov et al., 2017), the design of this study provides greater sensitivity to discontinuities in the compression behavior of ϵ -Fe₇N₃ due to denser data coverage with pressure intervals of ~ 1 GPa (Figure 3a) and quasi-hydrostatic medium.

Table 1
Equation of State Parameters of ϵ -Fe₇N₃ and γ' -Fe₄N

Phase	Magnetism	P (GPa)	V_0 (Å ³)	K_0	K_0'	Method	Reference
ϵ -Fe ₇ N ₃	Magnetic (mixed spin)	0–40	86.55(2) ^a	160(2)	4.3(2)	DAC ^c	This study
ϵ -Fe ₇ N ₃	Nonmagnetic (low spin)	40–60	83.29(3)	232(9)	4.1(5)	DAC	This study
ϵ -Fe ₇ N ₃	-	0–51	86.04(10)	168(10)	5.7(2)	DAC	Adler and Williams (2005)
ϵ -Fe ₃ N _{1.26}	-	0–31	86.18(3)	163(2)	5.3(2)	MA ^d	Litasov et al. (2017)
ϵ -Fe ₃ N _{1.25}	Magnetic (mixed spin)	0–100	81.35	224(1)	4.30(5)	DFT-GGA ^e	Popov et al. (2015)
ϵ -Fe ₃ N _{1.25}	Nonmagnetic	0–500	77.44	303(1)	4.38(1)	DFT-GGA	Popov et al. (2015)
γ' -Fe ₄ N	-	0–60	54.82(2)	152(2)	4.0(1)	DAC	This study
γ' -Fe ₄ N	-	0–31	54.95(22)	155(3)	4 ^b	DAC	Adler and Williams (2005)
γ' -Fe ₄ N	-	0–33	54.81	154(3)	5.3(1)	DAC	Guo et al. (2013)
γ' -Fe ₄ N	-	22–60	54.95 ^b	169(6)	4.1(4)	DAC	Breton et al. (2019)
γ' -Fe ₄ N	-	-	-	166(1)	4.2(1)	DFT-GGA	Niewa, Rau, Wosylus, Meier, Wessel, et al. (2009)
γ' -Fe ₄ N	Magnetic	-	54.64	192(1)	-	FP-TEC ^f	Gressmann et al. (2007)
γ' -Fe ₄ N	Magnetic (mixed spin)	0–200	54.10	152(4)	5.41(17)	DFT-GGA	Popov et al. (2015)
γ' -Fe ₄ N	Nonmagnetic	0–500	49.25	285(3)	4.38(1)	DFT-GGA	Popov et al. (2015)

^aNumbers in parentheses are uncertainties on the last digits. ^bFixed value. ^cDiamond anvil cell. ^dMultianvil press. ^eDensity functional theory-generalized gradient approximation. ^fFirst-principles total-energy calculations.

Given the compression and magnetic behaviors described above, we separately fit the P - V data of ϵ -Fe₇N₃ using third-order Birch-Murnaghan equation of state (BM3-EoS) over two distinct pressure ranges above and below 40 GPa, and that of γ' -Fe₄N with a single curve for the entire data range in order to better describe the compressibility. Below 40 GPa ϵ -Fe₇N₃ has a continuously evolving, mixed-spin state, and the resulting EoS parameters are expected to be anomalously soft relative to the high-spin state. The parameters of the BM3-EoS, isothermal bulk modulus, K_0 , its pressure derivative, K_0' , and volume at 1 bar V_0 , obtained in the present study and previous studies are summarized in Table 1.

The BM3-EoS parameters of magnetic, mixed-spin ϵ -Fe₇N₃ obtained by fitting the P - V data from 1 bar and 40 GPa to BM3-EoS are compared with previous experimental constraints on the same stoichiometry (Adler & Williams, 2005; Litasov et al., 2017) (Table 1), showing consistency with the parameters obtained by (Litasov et al., 2017) within uncertainties, whereas 5% (or higher given the tradeoff between K_0 and K_0') elastic softer than that constrained by (Adler & Williams, 2005). Figure 3a shows our measured P - V data are in good agreement with data obtained by Litasov et al. (2017) from 1 bar to 31 GPa using a multianvil press, supporting a quasi-hydrostatic conditions in this study. However, the volume data reported by Adler and Williams (2005) deviate from our measurements at pressures higher than 30 GPa, likely due to the nonhydrostatic stress supported by methanol:ethanol:water pressure transmitting medium. Properties predicted for magnetic ϵ -Fe₃N_{1.25} by density functional theory (Popov et al., 2015) are significantly offset, with V_0 lower by 6% and K_0 higher by 38% compared to experimental constraints. For nonmagnetic, low-spin ϵ -Fe₇N₃, EoS fit for the data from 40 to 60 GPa with a fixed V_0 [83.28(±2) Å³] constrained by g - G plot (Figure 3b) yields K_0 45% higher than that of magnetic phase (22% increase in bulk modulus at 40 GPa, Figure 5), indicating a significant elastic stiffening associated with the magnetic collapse. Popov et al. (2015) predicted a magnetic-nonmagnetic transition of ϵ -Fe₇N₃ completed at 130 GPa, inducing a 35% difference in K_0 , but both the transition pressure and bulk modulus are much higher than our constraints (Table 1). An increase in incompressibility induced by the collapse of magnetic momentum has been observed in other Fe-alloys such as Fe₃C (Prescher et al., 2012) and Fe₃P (Lai et al., 2020). These alloys are also not observed to soften during the spin transition, in contrast to pressure-induced Invar behavior of Fe alloys such as Fe-Ni (Dubrovinsky et al., 2001) and Fe₇C₃ (Chen et al., 2012) which undergo elastic softening during the transition followed by reaching a stiffer nonmagnetic state.

The EoS parameters of γ' -Fe₄N derived by fitting the measured P - V data up to 60 GPa to BM3-EoS agree with the parameters reported by Adler and Williams (2005) and Guo et al. (2013) within uncertainties (Table 1). However, the K_0 reported by Breton et al. (2019), 169(±6) GPa, is 13% higher than our result, and the measured volumes deviate from our measurements as illustrated in Figure 4a. This discrepancy can be attributed to nonhydrostatic conditions in the sample chamber produced using KCl as the pressure transmitting medium, and lack of data at 0–20 GPa regime may cause a fitting bias when fixing the V_0

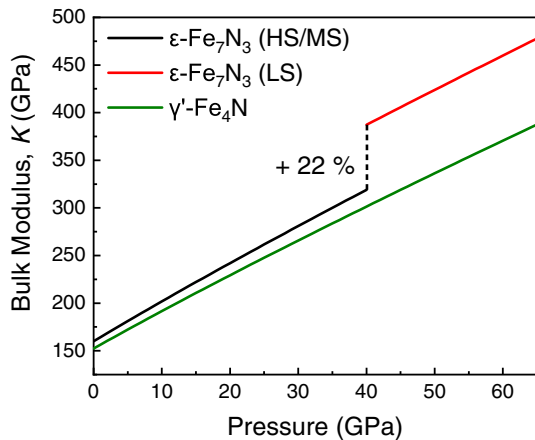


Figure 5. Isothermal bulk modulus (K) of high-spin and mixed-spin (magnetic) state ϵ - Fe_7N_3 (black curve), low-spin (nonmagnetic) state ϵ - Fe_7N_3 (red curve), and γ' - Fe_4N (dark green curve) at 300 K as a function of pressure, calculated from the fitted BM-EOS parameters (Table 1). The magnetic to nonmagnetic transition of ϵ - Fe_7N_3 induces +22% increase in incompressibility at 40 GPa.

these compounds have fully reached a nonmagnetic state by 43 and 34 GPa, respectively. Iron-light element compounds and alloys in Fe-P, Fe-C, Fe-S, and other systems typically undergo a transition from ferromagnetic to paramagnetic state before the transition to a fully nonmagnetic state (Chen et al., 2014, 2018; Gu et al., 2016; Lin, Fei, et al., 2004), so it can be inferred that an additional FM-PM transition may take place in Fe-N compounds below the completion of the spin transition. The only previous experimental investigation of pressure-induced magnetic transitions of iron nitrides was conducted by Ishimatsu et al. (2003) on γ' - Fe_4N using XMCD, and showed the spin polarization was suppressed by pressure and finally vanished at 24 GPa. This loss of spin polarization was interpreted as a ferromagnetic to paramagnetic transition. This combined with our XES results indicates that paramagnetic γ' - Fe_4N has completely transitioned to the nonmagnetic state by 34 GPa. However, the pressure of any FM-PM transition in ϵ - Fe_7N_3 has not been directly observed by experiments, due to the lack of studies using Mössbauer spectroscopy or XMCD.

Indirect measurement of a FM-PM transition in Fe-N compounds through compression behavior has been inconclusive, and in iron-light element compounds more broadly, effects of FM-PM transitions on compressibility are either not observed or controversial. For example, the pressure of the FM-PM transition in Fe_3C was determined at ~ 8 – 10 GPa using Mössbauer spectroscopy, and no effect on the compression behavior was observed (Prescher et al., 2012); whereas Litasov et al. (2013) observed this transition at ~ 7 – 9 GPa based on anomalous compression behavior of the a axis, and proposed an elastic stiffening. Conditions of FM-PM transitions identified in previous work on ϵ - Fe_7N_3 and γ' - Fe_4N do not correspond to any significant changes in incompressibility.

In contrast, most Fe-light element compounds and alloys do exhibit stiffening after completing the transition to nonmagnetic state. Comparison between compression behavior and spin transition of ϵ - Fe_7N_3 reveals elastic stiffening associated with magnetic-nonmagnetic (i.e., high to low spin) transition at ~ 40 GPa. Similar behaviors have been observed and predicted in iron alloys, such as Fe-C, Fe-P, Fe-S systems (see section 4.2 for more discussion), which consistently show that the PM-NM transition induces elastic stiffening, whereas elastic softening of Fe_7C_3 is due to Invar behavior (Chen et al., 2012, 2014; Mookherjee et al., 2011). γ' - Fe_4N is unique among the Fe-light element compounds and alloys discussed here: while the pressure of the PM-NM transition is constrained through complementary spectroscopic methods, it has no significant effect on compression behavior.

Ab initio calculations of magnetic states of Fe-N compounds have predicted magnetic transition pressures much higher than those observed in experiments. The transitions from magnetic to nonmagnetic states of ϵ - $\text{Fe}_3\text{N}_{1.25}$ and γ' - Fe_4N at 0 K were predicted to complete at 130 and 250 GPa, respectively (Popov et al., 2015). Popov et al. (2015) also predicted significant volume collapse of iron nitrides due to the changes in the

constrained by Adler and Williams (2005). K_0 computed by density functional theory with generalized gradient approximation studies (Niewa, Rau, Wosylus, Meier, Wessel, et al., 2009; Popov et al., 2015) spans a range from 0% to 9% higher than that constrained by experiments, whereas the K_0 calculated from single-crystal elastic constants by first-principles total-energy method is 26% higher than that constrained by experiments.

Popov et al. (2015) predicted a magnetic-nonmagnetic transition of γ' - Fe_4N completed at 250 GPa, inducing a +87.5% jump of K_0 , in contrast to our observation of this transition at much lower pressure with no significant effect on elasticity. γ' - Fe_4N is also less incompressible than both magnetic and nonmagnetic ϵ - Fe_7N_3 , which leads to its destabilization at pressures above 60 GPa (Breton et al., 2019).

4. Discussion

4.1. Magnetic Transitions of ϵ - Fe_7N_3 and γ' - Fe_4N

Both ϵ - Fe_7N_3 and γ' - Fe_4N adopt a ferromagnetic state at 1 bar with Curie temperatures of 400 K (Leineweber et al., 2001) and 750 K (Wriedt et al., 1987), respectively. Based on the XES observations described above,

magnetic moment, which is in contrast to experimental observations, and not reported in previous ab initio calculations on iron carbides (Mookherjee et al., 2011; Vocadlo et al., 2002) although both studies used the generalized gradient approximation (GGA).

The difference in magneto-elastic coupling behavior between ϵ -Fe₇N₃ and γ' -Fe₄N may be attributed to the difference in strengths of Fe-N bonds associated with the crystal structures. In the idealized model of the crystal structure of ϵ -Fe₃N, the iron atoms are distributed according to hexagonal close packing (ϵ -Fe) and nitrogen atoms occupy one third of octahedral voids between the iron layers in an ordered manner (Figure S3). However, nonstoichiometric ϵ -Fe₃N_x ($0.75 < x < 1.4$) exhibits a broad homogeneity range together with some entropy-driven transfer of nitrogen to further octahedral voids (Niewa, Rau, Wosylus, Meier, Hanfland, et al., 2009). Iron atoms in γ' -Fe₄N are distributed according to the cubic close packing (γ -Fe) and nitrogen atoms occupy one fourth of octahedral voids (Figure S3). The resulting different 3d band structure affected by stronger 3p-3d hybridization of Fe and N in ϵ -Fe₇N₃ leads to a magnetic to nonmagnetic transition pressure of ϵ -Fe₇N₃ ~10 GPa higher than that observed in γ' -Fe₄N (Figure 2). The difference in transition pressures may also be due to the relationship between anisotropic compressibility and the orientation of the magnetic moment relative to the crystal structure. For ϵ -Fe₇N₃, a collinear ferromagnetic arrangement of moments was determined to be parallel to the *c* axis by neutron diffraction measurements (Robbins & White, 1964), and *c* axis is more incompressible than *a* axis (Shi et al., 2013) (*c/a* ratio increases with pressure, Figure S4); while for γ' -Fe₄N, magnetic arrangement of moments was proposed to be parallel to the *a* axis (Costa-Krämer et al., 2004), which is the stiffest direction (Gressmann et al., 2007). To better understand the effect of spin transition on elastic anisotropy of both iron nitrides, further measurements on elastic constants up to spin transition pressures are necessary.

4.2. Magneto-Elastic Coupling in Fe-Light Element Alloys/Compounds

Previous studies have identified multiple candidate Fe alloys and light element compounds that can match the observed density and elastic properties of Earth's core (reviewed by Hirose et al., 2013; Li & Fei, 2014), and many of them undergo pressure-induced magnetic transitions with effects on elasticity (reviewed by Caracas, 2016). As a result, the extrapolation of density and velocity of ambient or low-pressure data to Earth's core conditions may be misleading, and experiments at higher pressures and temperatures are critical. However, the pressure of magnetic collapse and its coupling with elastic properties were inconsistent in previous results: for example, the pressure of PM to NM transition for Fe₃C from different studies spans a large range of 22 to 68 GPa (reviewed by Chen & Li, 2016). This inconsistency is partially caused by different criteria for magnetic transitions constrained using different methods.

The spin transition (or PM-NM transition) of ionic or covalent materials is usually accompanied by a change in interatomic distance due to a decrease in the size of the Fe atom, which results in a volume collapse (Lin et al., 2013). In Fe alloys, the effect of the spin transition on structure and volume is subtle, leading to difficulties in detection. For direct comparison to this work on ϵ -Fe₇N₃ and γ' -Fe₄N, in which complementary methods determine the collapse of magnetic momentum and changes in compression behavior, we reexamine evidence for magnetic collapse and its effect on the compression behavior of other Fe-light element compounds Fe₃S, Fe₃P, Fe₇C₃, and Fe₃C, for which previous authors have obtained both XES measurements and dense *P-V* data coverage up to ~150 GPa.

Fe₃S remains in the tetragonal structure up to at least 200 GPa, with the completion of magnetic-nonmagnetic transition determined to occur at ~25 GPa by XES (Shen et al., 2003). A previous study argued that the magnetic transition did not affect the structure or compression behavior of Fe₃S (Kamada et al., 2014). However, a *g-G* plot (Figure 6a) of the compression measurements from Chen et al. (2007), Kamada et al. (2014), and Seagle et al. (2006) illustrates a discontinuity in compression behavior at ~67 GPa, which could have been induced by a magnetic collapse. The spin transition pressure may be underestimated by XES (Shen et al., 2003), due to the limitations of the spectral analysis method (no low spin reference applied) and the limited pressure range (up to 30 GPa) of the study.

Fe₃P is isostructural with the Fe₃S tetragonal phase at ambient conditions, and in situ XRD patterns suggest no structural phase transition up to 111 GPa (Lai et al., 2020), although the structural evolution of Fe₃P upon compression remains controversial (Gu et al., 2014; Sagatov et al., 2020; Scott et al., 2007). The *g-G* plot based on the *P-V* measurements by Lai et al. (2020) shows an increase in incompressibility at ~38 GPa (Figure 6b),

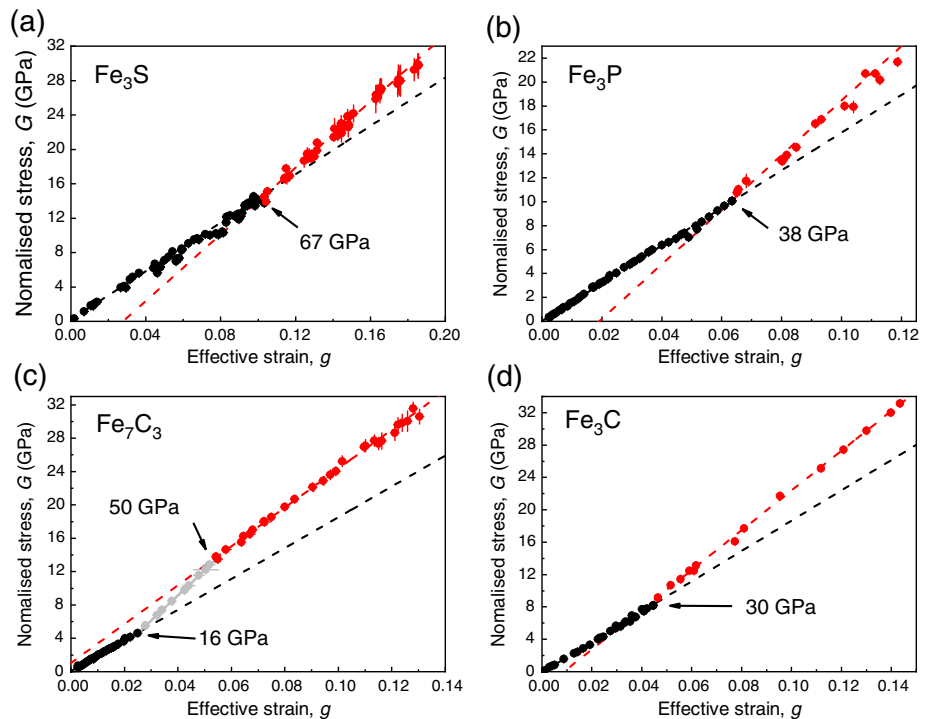


Figure 6. Normalized stress G as a function of effective strain g for (a) Fe_3S (Chen et al., 2007; Kamada et al., 2014; Seagle et al., 2006), (b) Fe_3P (Lai et al., 2020), (c) Fe_7C_3 (Chen et al., 2012; Liu et al., 2016), and (d) Fe_3C (Li et al., 2002; Litasov et al., 2013; Ono & Mibe, 2010; Sata et al., 2010). Dashed lines are linear fits to g - G , and the discontinuity in compression behavior corresponds to the change of slope of the linearized g - G plot.

which coincides with the pressure of magnetic spin momentum collapse determined by XES (Gu et al., 2016). Lai et al. (2020) propose the completion of magnetic-nonmagnetic transition occurred at 21 GPa based on the disappearance of fast oscillation in Mössbauer spectra, which can be attributed to a ferromagnetic to paramagnetic transition.

Fe_7C_3 adopts a hexagonal structure from ~ 7 –8 to 167 GPa (Chen et al., 2012; Lord et al., 2009), and its magneto-elastic coupling effects have been thoroughly studied. By plotting the measurements from Chen et al. (2012) and Liu et al. (2016) as a g - G relation, an elastic stiffening occurs at 16 GPa and a softening occurs at 50 GPa (Figure 6c). These discontinuities in the compression behavior can be explained by a non-collinear to paramagnetic transition proposed by Liu et al. (2016) and a magnetic collapse determined by XES (Chen et al., 2014), respectively.

Fe_3C , known as the mineral cohenite, has an orthorhombic structure with $Pnma$ space group, and no structural change in Fe_3C was observed up to 187 GPa (Sata et al., 2010). The pressure of PM-NM (or high- to low-spin) transition in Fe_3C determined by XES has ranged widely from ~ 25 GPa by Lin, Struzhkin, et al. (2004) to ~ 50 GPa by Chen et al. (2018). The g - G plot of P - V measurements combined from Li et al. (2002), Litasov et al. (2013), Ono and Mibe (2010), and Sata et al. (2010) indicates an elastic stiffening occurring at ~ 30 GPa (Figure 6d), which is consistent with the decreasing of the emission satellite peak intensity until 30 GPa observed by Lin, Struzhkin, et al. (2004). We thus interpret the discontinuity in compression behavior of Fe_3C at ~ 30 GPa is induced by the completion of the spin transition.

In summary, XES and g - G plots generally reveal the collapse of magnetic moment and effects on the compression behavior of Fe-light element alloys and compounds, which are candidate constituents of the Earth's core. A change in incompressibility induced by magnetic-nonmagnetic transitions may be common throughout Fe-light element compound systems, whereas the effects from FM-PM transition on compression are not significant for most compounds. To extrapolate physical properties to conditions of Earth's core, low-spin/nonmagnetic thermodynamic parameters should be used, and the effects of temperature should be considered. It has been shown that the pressure range for mixed-spin ferropericlase [$(\text{Mg}_{0.75}\text{Fe}_{0.25})\text{O}$]

is broadened by 30 GPa as the temperature increases from 300 to 2000 K (Z. Mao et al., 2011). The thermal equations of state of Fe-light element alloys up to Earth's core conditions await further investigation.

4.3. Implications for Iron Alloys in Earth's and Planetary Cores

Our results suggest that although magnetic-to-nonmagnetic transitions do not produce sharp discontinuities in the compression behavior of Fe_7N_3 , Fe_3S , Fe_3P , Fe_7C_3 , and Fe_3C , their effect is nonnegligible and additional tools, such as XES experiments and an analysis of g - G plots, are required to accurately determine the pressure range of the magnetic transitions. Consequently, the effect of magnetic transitions on the compression behavior of other light-element-bearing iron compounds may have been overlooked in previous experiments based only on an analysis of the pressure-volume data (e.g., Kamada et al., 2014). The effects of magnetic transitions should not be ignored when investigating the roles of iron alloys in Earth's and planetary cores under relevant conditions.

For example, distribution of iron isotopes in the Earth, which has been used to trace planetary differentiation processes, is dependent on isotope fractionation between various candidate host phases for iron in planetary cores and silicate melts under different pressure, temperature, composition, and oxygen fugacity conditions (Dauphas et al., 2017). Pressure effects on iron isotope fractionation determined by nuclear resonant inelastic X-ray scattering spectroscopy measurements have been different for different alloys, which is explained by differences in bond strength between combinations of iron with different alloying elements (Liu et al., 2017; Shahar et al., 2016). Considering the effects of magnetic transitions on bond lengths and strengths of iron alloys presented in this study, magnetic transitions of iron alloys may impact the pressure dependence of the $^{57/54}\text{Fe}$ β factor (reduced partition function ratios) and thus the iron isotope fractionation over Earth's history.

The pressure conditions of the magnetic transitions in ϵ - Fe_7N_3 , Fe_3S , Fe_3P , Fe_7C_3 , and Fe_3C revealed by this study overlap with the moderate P - T range of the cores of relatively small planets, such as Mercury (~ 8 to 40 GPa, ~ 1700 to 2200 K) (Chen et al., 2008) and Mars (~ 24 to 42 GPa, ~ 2000 to 2600 K) (Fei & Bertka, 2005). Whether Mercury and Mars have fully molten cores (Margot et al., 2007; Yoder et al., 2003) or include solid inner cores (Genova et al., 2019; Stevenson, 2001) is under debate. In either case, planetary cooling may entail a present and/or past "snowing-core" scenario where iron-rich solids nucleate at the liquidus and sink or rise based on buoyancy. Minor solid iron alloys may thus significantly affect planetary core dynamics through powering magnetic dynamos (Breuer et al., 2015, and references therein). The effects of magnetic transition on physical properties (such as incompressibility and density; Figure S5) of these candidate constituents of planetary cores may play an important role in deciphering the potential role of N, C, S, and P in these planetary cores.

5. Conclusions

In this work, we report spin/magnetic transitions and compressibility of ϵ - Fe_7N_3 and γ' - Fe_4N , the two stable iron nitrides at ambient conditions. Synchrotron XES and XRD measurements were carried out up to 60 GPa at 300 K using DAC. The completion of magnetic collapse in ϵ - Fe_7N_3 and γ' - Fe_4N is observed at 43 and 34 GPa, respectively, indicated by the completion of high- to low-spin state transition. Comparing spin transition and discontinuities in compression behavior monitored by g - G plot, the completion of spin transition induces elastic stiffening in ϵ - Fe_7N_3 by 22% at ~ 40 GPa, but has no resolvable effect on the compression behavior of γ' - Fe_4N . Accordingly, fitting P - V data to BM3-EoS yields $V_0 = 86.55 \pm 0.02$ (\AA^3), $K_0 = 160 \pm 2$ GPa, and $K_0' = 4.3 \pm 0.2$ for magnetic, mixed-spin ϵ - Fe_7N_3 ; $V_0 = 83.29 \pm 0.03$ (\AA^3), $K_0 = 232 \pm 9$ GPa, and $K_0' = 4.1 \pm 0.5$ for nonmagnetic, low-spin ϵ - Fe_7N_3 ; $V_0 = 54.82 \pm 0.02$ (\AA^3), $K_0 = 152 \pm 2$ GPa, and $K_0' = 4.0 \pm 0.1$ for γ' - Fe_4N within the investigated pressure range.

Using the same protocol, we reexamine evidence for magnetic collapse and its effect on the compression behavior of other Fe-light element compounds as candidate components of terrestrial planet's core, Fe_3S , Fe_3P , Fe_7C_3 , and Fe_3C . We summarize previous reported dense P - V data up to ~ 150 GPa and comparing with XES measurements, which indicate the completion of the magnetic transition in Fe_3S , Fe_3P , and Fe_7C_3 is at about 67, 38, 50, and 30 GPa, respectively. The completion of the magnetic transition of Fe_3S and Fe_3P induces elastic stiffening, whereas that of Fe_7C_3 induces elastic softening. The changes of incompressibility

induced by magnetic-nonmagnetic transition may have potential implications in deciphering the role of iron-light element alloys in Earth's and planetary cores.

Data Availability Statement

All the data to produce the results are available on Zenodo (<https://doi.org/10.5281/zenodo.3959348>).

Acknowledgments

We thank two anonymous reviewers for constructive comments and suggestions that improved the manuscript, and Dr. Stephen Parman for editorial handling and comments. S. M. Dorfman acknowledges support for this work from NSF EAR-1751664. J. Li acknowledges support from NSF EAR-1763189 and AST-1344133. Beamtime for XES was provided through the Capital-DOE Alliance Center. XES measurements were performed at HPCAT (Sector 16), Advanced Photon Source (APS), Argonne National Laboratory. HPCAT operations are supported by DOE-NNSA's Office of Experimental Sciences. XRD measurements performed at GeoSoilEnviroCARS (The University of Chicago, Sector 13), Advanced Photon Source (APS), Argonne National Laboratory. GeoSoilEnviroCARS is supported by the National Science Foundation-Earth Sciences (EAR-1634415) and Department of Energy-GeoSciences (DE-FG02-94ER14466). Use of the COMPRES-GSECARS gas loading system and the PX2 program was supported by COMPRES under NSF Cooperative Agreement EAR-1661511 and by GSECARS through NSF grant EAR-1634415 and DOE grant DE-FG02-94ER14466. This research used resources of the Advanced Photon Source, a U.S. Department of Energy (DOE) Office of Science User Facility operated for the DOE Office of Science by Argonne National Laboratory under Contract No. DE-AC02-06CH11357.

References

- Adler, J. F., & Williams, Q. (2005). A high-pressure X-ray diffraction study of iron nitrides: Implications for Earth's core. *Journal of Geophysical Research*, *110*, B01203. <https://doi.org/10.1029/2004JB003103>
- Angel, R. J. (2000). Equations of state. *High-Temperature and High-Pressure Crystal Chemistry*, *41*(1), 35–59. <https://doi.org/10.2138/rmg.2000.41.2>
- Badro, J., Fiquet, G., Guyot, F., Rueff, J. P., Struzhkin, V. V., Vanko, G., & Monaco, G. (2003). Iron partitioning in Earth's mantle: Toward a deep lower mantle discontinuity. *Science*, *300*(5620), 789–791. <https://doi.org/10.1126/science.1081311>
- Badro, J., Fiquet, G., Struzhkin, V. V., Somayazulu, M., Mao, H. K., Shen, G., & Le Bihan, T. (2002). Nature of the high-pressure transition in Fe₂O₃ hematite. *Physical Review Letters*, *89*(20), 205,504. <https://doi.org/10.1103/PhysRevLett.89.205504>
- Badro, J., Rueff, J. P., Vanko, G., Monaco, G., Fiquet, G., & Guyot, F. (2004). Electronic transitions in perovskite: Possible nonconvecting layers in the lower mantle. *Science*, *305*(5682), 383–386. <https://doi.org/10.1126/science.1098840>
- Birch, F. (1952). Elasticity and constitution of the Earth's interior. *Journal of Geophysical Research*, *57*(2), 227–286. <https://doi.org/10.1029/JZ057i002p00227>
- Breton, H., Komabayashi, T., Thompson, S., Potts, N., McGuire, C., Suehiro, S., et al. (2019). Static compression of Fe₄N to 77 GPa and its implications for nitrogen storage in the deep Earth. *American Mineralogist*, *104*(12), 1781–1787. <https://doi.org/10.2138/am-2019-7065>
- Breuer, D., Rueckriemen, T., & Spohn, T. (2015). Iron snow, crystal floats, and inner-core growth: Modes of core solidification and implications for dynamos in terrestrial planets and moons. *Progress in Earth and Planetary Science*, *2*(1). <https://doi.org/10.1186/s40645-015-0069-y>
- Caracas, R. (2016). Crystal structures of Core materials. *Deep Earth: Physics and Chemistry of the Lower Mantle and Core*, *217*, 57–68.
- Chen, B., Gao, L., Funakoshi, K., & Li, J. (2007). Thermal expansion of iron-rich alloys and implications for the Earth's core. *Proceedings of the National Academy of Sciences*, *104*(22), 9162–9167. <https://doi.org/10.1073/pnas.0610474104>
- Chen, B., Gao, L. L., Lavina, B., Dera, P., Alp, E. E., Zhao, J. Y., & Li, J. (2012). Magneto-elastic coupling in compressed Fe₇C₃ supports carbon in Earth's inner core. *Geophysical Research Letters*, *39*, L18301. <https://doi.org/10.1029/2012GL052875>
- Chen, B., Lai, X. J., Li, J., Liu, J. C., Zhao, J. Y., Bi, W. L., et al. (2018). Experimental constraints on the sound velocities of cementite Fe₃C to core pressures. *Earth and Planetary Science Letters*, *494*, 164–171. <https://doi.org/10.1016/j.epsl.2018.05.002>
- Chen, B., & Li, J. (2016). Carbon in the core. *Deep Earth: Physics and Chemistry of the Lower Mantle and Core*, 277–288.
- Chen, B., Li, J., & Hauck, S. A. (2008). Non-ideal liquidus curve in the Fe-S system and Mercury's snowing core. *Geophysical Research Letters*, *35*, L07201. <https://doi.org/10.1029/2008GL033311>
- Chen, B., Li, Z., Zhang, D., Liu, J., Hu, M. Y., Zhao, J., et al. (2014). Hidden carbon in Earth's inner core revealed by shear softening in dense Fe₇C₃. *Proceedings of the National Academy of Sciences*, *111*(50), 17,755–17,758. <https://doi.org/10.1073/pnas.1411154111>
- Costa-Krämer, J. L., Borsa, D. M., Garcia-Martín, J. M., Martín-González, M. S., Boerma, D. O., & Briones, F. (2004). Structure and magnetism of single-phase epitaxial γ'-Fe₄N. *Physical Review B*, *69*(14). <https://doi.org/10.1103/PhysRevB.69.144402>
- Dauphas, N., John, S. G., & Rouxel, O. (2017). Iron isotope systematics. *Reviews in Mineralogy and Geochemistry*, *82*(1), 415–510.
- De Waele, S., Lejaeghere, K., Leunis, E., Duprez, L., & Cottenier, S. (2019). A first-principles reassessment of the Fe-N phase diagram in the low-nitrogen limit. *Journal of Alloys and Compounds*, *775*, 758–768. <https://doi.org/10.1016/j.jallcom.2018.09.356>
- Dewaele, A., Loubeyre, P., Occelli, F., Mezouar, M., Dorogokupets, P. I., & Torrent, M. (2006). Quasihydrostatic equation of state of iron above 2 Mbar. *Physical Review Letters*, *97*(21), 215,504. <https://doi.org/10.1103/PhysRevLett.97.215504>
- Dirba, I., Yazdi, M. B., Radeţinac, A., Komissinskiy, P., Flege, S., Gutfleisch, O., & Alff, L. (2015). Growth, structure, and magnetic properties of γ'-Fe₄N thin films. *Journal of Magnetism and Magnetic Materials*, *379*, 151–155. <https://doi.org/10.1016/j.jmmm.2014.12.033>
- dos Santos, A. V., & Samudio Pérez, C. A. (2016). Ab initio investigation of the substitution effects of 2p elements on the electronic structure of γ'-Fe₄X (X = B, C, N, and O) in the ground state. *Journal of Materials Research*, *31*(2), 202–212. <https://doi.org/10.1557/jmr.2015.394>
- Dubrovinsky, L., Dubrovinskaia, N., Abrikosov, I. A., Vennstrom, M., Westman, F., Carlson, S., et al. (2001). Pressure-induced invar effect in Fe-Ni alloys. *Physical Review Letters*, *86*(21), 4851–4854. <https://doi.org/10.1103/PhysRevLett.86.4851>
- Fei, Y., & Bertka, C. (2005). Planetary science. The interior of Mars. *Science*, *308*(5725), 1120–1121. <https://doi.org/10.1126/science.1110531>
- Fei, Y., Ricolleau, A., Frank, M., Mibe, K., Shen, G., & Prakapenka, V. (2007). Toward an internally consistent pressure scale. *Proceedings of the National Academy of Sciences*, *104*(22), 9182–9186. <https://doi.org/10.1073/pnas.0609013104>
- Genova, A., Goossens, S., Mazarico, E., Lemoine, F. G., Neumann, G. A., Kuang, W., et al. (2019). Geodetic evidence that Mercury has a solid inner core. *Geophysical Research Letters*, *46*, 3625–3633. <https://doi.org/10.1029/2018GL081135>
- Gressmann, T., Wohlschlägel, M., Shang, S., Welzel, U., Leineweber, A., Mittemeijer, E. J., & Liu, Z. K. (2007). Elastic anisotropy of γ'-Fe₄N and elastic grain interaction in γ'-Fe₄N_{1-y} layers on α-Fe: First-principles calculations and diffraction stress measurements. *Acta Materialia*, *55*(17), 5833–5843. <https://doi.org/10.1016/j.actamat.2007.07.001>
- Gu, T., Fei, Y., Wu, X., & Qin, S. (2014). High-pressure behavior of Fe₃P and the role of phosphorus in planetary cores. *Earth and Planetary Science Letters*, *390*, 296–303. <https://doi.org/10.1016/j.epsl.2014.01.019>
- Gu, T., Fei, Y., Wu, X., & Qin, S. (2016). Phase stabilities and spin transitions of Fe₃(S_{1-x}P_x) at high pressure and its implications in meteorites. *American Mineralogist*, *101*(1), 205–210. <https://doi.org/10.2138/am-2016-5466>
- Guo, K., Rau, D., von Appen, J., Prots, Y., Schnelle, W., Dronskowski, R., et al. (2013). High pressure high-temperature behavior and magnetic properties of Fe₄N: Experiment and theory. *High Pressure Research*, *33*(3), 684–696. <https://doi.org/10.1080/08957959.2013.809715>
- Hirose, K., Labrosse, S., & Hernlund, J. (2013). Composition and state of the core. In R. Jeanloz (Ed.), *Annual Review of Earth and Planetary Sciences* (Vol. 41, pp. 657–691). Palo Alto: Annual Reviews.

- Hrubciak, R., Sinogeikin, S., Rod, E., & Shen, G. (2015). The laser micro-machining system for diamond anvil cell experiments and general precision machining applications at the High Pressure Collaborative Access Team. *Review of Scientific Instruments*, 86(7), 072202. <https://doi.org/10.1063/1.4926889>
- Ishimatsu, N., Maruyama, H., Kawamura, N., Suzuki, M., Ohishi, Y., Ito, M., et al. (2003). Pressure-induced magnetic transition in Fe₄N probed by Fe K-edge XMCD measurement. *Journal of the Physical Society of Japan*, 72(9), 2372–2376. <https://doi.org/10.1143/JPSJ.72.2372>
- Jeanloz, R. (1981). Finite-strain equation of state for high-pressure phases. *Geophysical Research Letters*, 8(12), 1219–1222. <https://doi.org/10.1029/GL008i012p01219>
- Kamada, S., Ohtani, E., Terasaki, H., Sakai, T., Takahashi, S., Hirao, N., & Ohishi, Y. (2014). Equation of state of Fe₃S at room temperature up to 2 megabars. *Physics of the Earth and Planetary Interiors*, 228, 106–113. <https://doi.org/10.1016/j.pepi.2013.11.001>
- Kaminsky, F., & Wirth, R. (2017). Nitrides and carbonitrides from the lowermost mantle and their importance in the search for Earth's "lost" nitrogen. *American Mineralogist*, 102(8), 1667–1676. <https://doi.org/10.2138/am-2017-6101>
- Klotz, S., Chervin, J. C., Munsch, P., & Le Marchand, G. (2009). Hydrostatic limits of 11 pressure transmitting media. *Journal of Physics D: Applied Physics*, 42(7), 075413. <https://doi.org/10.1088/0022-3727/42/7/075413>
- Kusakabe, M., Hirose, K., Sinmyo, R., Kuwayama, Y., Ohishi, Y., & Helffrich, G. (2019). Melting curve and equation of state of β-Fe₇N₃: Nitrogen in the core? *Journal of Geophysical Research: Solid Earth*, 124, 3448–3457. <https://doi.org/10.1029/2018JB015823>
- Lai, X., Zhu, F., Liu, Y., Bi, W., Zhao, J., Alp, E. E., et al. (2020). Elastic and magnetic properties of Fe₃P up to core pressures: Phosphorus in the Earth's core. *Earth and Planetary Science Letters*, 531, 115974. <https://doi.org/10.1016/j.epsl.2019.115974>
- Le Bail, A. (2012). Whole powder pattern decomposition methods and applications: A retrospective. *Powder Diffraction*, 20(4), 316–326. <https://doi.org/10.1154/1.2135315>
- Leineweber, A., Jacobs, H., Hüning, F., Lueken, H., & Kockelmann, W. (2001). Nitrogen ordering and ferromagnetic properties of ε-Fe₃N_{1+x} (0.10 ≤ x ≤ 0.39) and ε-Fe₃(N_{0.80}Co_{0.20})_{1.38}. *Journal of Alloys and Compounds*, 316(1–2), 21–38. [https://doi.org/10.1016/S0925-8388\(00\)01435-3](https://doi.org/10.1016/S0925-8388(00)01435-3)
- Li, J., & Fei, Y. (2014). Experimental constraints on core composition. In H. D. Holland, & K. K. Turekian (Eds.), *Treatise on Geochemistry* (pp. 527–557). Oxford: Elsevier.
- Li, J., Mao, H. K., Fei, Y., Gregoryanz, E., Eremets, M., & Zha, C. S. (2002). Compression of Fe₃C to 30 GPa at room temperature. *Physics and Chemistry of Minerals*, 29(3), 166–169. <https://doi.org/10.1007/s00269-001-0224-4>
- Lin, J.-F., Fei, Y., Sturhahn, W., Zhao, J., Mao, H.-k., & Hemley, R. J. (2004). Magnetic transition and sound velocities of Fe₃S at high pressure: Implications for Earth and planetary cores. *Earth and Planetary Science Letters*, 226(1–2), 33–40. <https://doi.org/10.1016/j.epsl.2004.07.018>
- Lin, J. F., Speziale, S., Mao, Z., & Marquardt, H. (2013). Effects of the electronic spin transitions of iron in lower mantle minerals: Implications for deep mantle geophysics and geochemistry. *Reviews of Geophysics*, 51, 244–275. <https://doi.org/10.1002/rog.20010>
- Lin, J. F., Struzhkin, V. V., Mao, H. K., Hemley, R. J., Chow, P., Hu, M. Y., & Li, J. (2004). Magnetic transition in compressed Fe₃C from X-ray emission spectroscopy. *Physical Review B*, 70(21). <https://doi.org/10.1103/PhysRevB.70.212405>
- Litasov, K. D., Sharygin, I. S., Dorogokupets, P. I., Shatskiy, A., Gavryushkin, P. N., Sokolova, T. S., et al. (2013). Thermal equation of state and thermodynamic properties of iron carbide Fe₃C to 31 GPa and 1473 K. *Journal of Geophysical Research: Solid Earth*, 118, 5274–5284. <https://doi.org/10.1002/2013JB010270>
- Litasov, K. D., Shatskiy, A., Ponomarev, D. S., & Gavryushkin, P. N. (2017). Equations of state of iron nitrides ε-Fe₃N_x and γ-Fe₄N_y to 30 GPa and 1200 K and implication for nitrogen in the Earth's core. *Journal of Geophysical Research: Solid Earth*, 122, 3574–3584. <https://doi.org/10.1002/2017JB014059>
- Liu, J., Dauphas, N., Roskosz, M., Hu, M. Y., Yang, H., Bi, W., et al. (2017). Iron isotopic fractionation between silicate mantle and metallic core at high pressure. *Nature Communications*, 8(1), 14377. <https://doi.org/10.1038/ncomms14377>
- Liu, J., Dorfman, S. M., Lv, M., Li, J., Zhu, F., & Kono, Y. (2019). Loss of immiscible nitrogen from metallic melt explains Earth's missing nitrogen. *Geochemical Perspectives Letters*, 18–22. <https://doi.org/10.7185/geochemlet.1919>
- Liu, J. C., Li, J., & Ikuta, D. (2016). Elastic softening in Fe₇C₃ with implications for Earth's deep carbon reservoirs. *Journal of Geophysical Research: Solid Earth*, 121, 1514–1524. <https://doi.org/10.1002/2015JB012701>
- Lord, O. T., Walter, M. J., Dasgupta, R., Walker, D., & Clark, S. M. (2009). Melting in the Fe–C system to 70 GPa. *Earth and Planetary Science Letters*, 284(1–2), 157–167. <https://doi.org/10.1016/j.epsl.2009.04.017>
- Mao, H. K., Xu, J., & Bell, P. M. (1986). Calibration of the ruby pressure gauge to 800 Kbar under quasi-hydrostatic conditions. *Journal of Geophysical Research*, 91(B5), 4673–4676. <https://doi.org/10.1029/JB091iB05p04673>
- Mao, Z., Lin, J. F., Liu, J., & Prakapenka, V. B. (2011). Thermal equation of state of lower-mantle ferropericlase across the spin crossover. *Geophysical Research Letters*, 38, L23308. <https://doi.org/10.1029/2011GL049915>
- Mao, Z., Lin, J. F., Yang, J., Wu, J. J., Watson, H. C., Xiao, Y. M., et al. (2014). Spin and valence states of iron in Al-bearing silicate glass at high pressures studied by synchrotron Mossbauer and X-ray emission spectroscopy. *American Mineralogist*, 99(2–3), 415–423. <https://doi.org/10.2138/am.2014.4490>
- Margot, J. L., Peale, S. J., Jurgens, R. F., Slade, M. A., & Holin, I. V. (2007). Large longitude libration of Mercury reveals a molten core. *Science*, 316(5825), 710–714. <https://doi.org/10.1126/science.1140514>
- McDonough, W. F., & Sun, S. S. (1995). The composition of the Earth. *Chemical Geology*, 120(3–4), 223–253. [https://doi.org/10.1016/0009-2541\(94\)00140-4](https://doi.org/10.1016/0009-2541(94)00140-4)
- Minobe, S., Nakajima, Y., Hirose, K., & Ohishi, Y. (2015). Stability and compressibility of a new iron-nitride β-Fe₇N₃ to core pressures. *Geophysical Research Letters*, 42, 5206–5211. <https://doi.org/10.1002/2015GL064496>
- Mookherjee, M., Nakajima, Y., Steinle-Neumann, G., Glazyrin, K., Wu, X. A., Dubrovinsky, L., et al. (2011). High-pressure behavior of iron carbide (Fe₇C₃) at inner core conditions. *Journal of Geophysical Research*, 116, B04201. <https://doi.org/10.1029/2010JB007819>
- Niewa, R., Rau, D., Wosylus, A., Meier, K., Hanfland, M., Wessel, M., et al. (2009). High-pressure, high-temperature single-crystal growth, ab initio electronic structure calculations, and equation of state of ε-Fe₃N_{1+x}. *Chemistry of Materials*, 21(2), 392–398. <https://doi.org/10.1021/cm802721k>
- Niewa, R., Rau, D., Wosylus, A., Meier, K., Wessel, M., Hanfland, M., et al. (2009). High-pressure high-temperature phase transition of γ'-Fe₄N. *Journal of Alloys and Compounds*, 480(1), 76–80. <https://doi.org/10.1016/j.jallcom.2008.09.178>
- Ono, S., & Mibe, K. (2010). Magnetic transition of iron carbide at high pressures. *Physics of the Earth and Planetary Interiors*, 180(1–2), 1–6. <https://doi.org/10.1016/j.pepi.2010.03.008>
- Poirier, J.-P. (1994). Light elements in the Earth's outer core: A critical review. *Physics of the Earth and Planetary Interiors*, 85(3–4), 319–337. [https://doi.org/10.1016/0031-9201\(94\)90120-1](https://doi.org/10.1016/0031-9201(94)90120-1)

- Popov, Z. I., Litasov, K. D., Gavryushkin, P. N., Ovchinnikov, S. G., & Fedorov, A. S. (2015). Theoretical study of γ' -Fe₄N and ϵ -Fe_xN iron nitrides at pressures up to 500 GPa. *JETP Letters*, 101(6), 371–375. <https://doi.org/10.1134/s0021364015060090>
- Prescher, C., Dubrovinsky, L., McCammon, C., Glazyrin, K., Nakajima, Y., Kantor, A., et al. (2012). Structurally hidden magnetic transitions in Fe₃C at high pressures. *Physical Review B*, 85(14), 140402. <https://doi.org/10.1103/PhysRevB.85.140402>
- Prescher, C., & Prakapenka, V. B. (2015). DIOPTAS: A program for reduction of two-dimensional X-ray diffraction data and data exploration. *High Pressure Research*, 35(3), 223–230. <https://doi.org/10.1080/08957959.2015.1059835>
- Rivers, M., Prakapenka, V. B., Kubo, A., Pullins, C., Holl, C. M., & Jacobsen, S. D. (2008). The COMPRES/GSECARS gas-loading system for diamond anvil cells at the Advanced Photon Source. *High Pressure Research*, 28(3), 273–292. <https://doi.org/10.1080/08957950802333593>
- Robbins, M., & White, J. G. (1964). Magnetic properties of epsilon-iron nitride. *Journal of Physics and Chemistry of Solids*, 25(7), 717. [https://doi.org/10.1016/0022-3697\(64\)90182-9](https://doi.org/10.1016/0022-3697(64)90182-9)
- Rubin, A. E., & Ma, C. (2017). Meteoritic minerals and their origins. *Geochemistry*, 77(3), 325–385. <https://doi.org/10.1016/j.chemer.2017.01.005>
- Sagatov, N., Gavryushkin, P. N., Inerbaev, T. M., & Litasov, K. D. (2019). New high-pressure phases of Fe₇N₃ and Fe₇C₃ stable at Earth's core conditions: Evidence for carbon-nitrogen isomorphism in Fe-compounds. *RSC Advances*, 9(7), 3577–3581. <https://doi.org/10.1039/c8ra09942a>
- Sagatov, N. E., Gavryushkin, P. N., Banayev, M. V., Inerbaev, T. M., & Litasov, K. D. (2020). Phase relations in the Fe-P system at high pressures and temperatures from ab initio computations. *High Pressure Research*, 40(2), 235–244. <https://doi.org/10.1080/08957959.2020.1740699>
- Sata, N., Hirose, K., Shen, G., Nakajima, Y., Ohishi, Y., & Hirao, N. (2010). Compression of FeSi, Fe₃C, Fe_{0.95}O, and FeS under the core pressures and implication for light element in the Earth's core. *Journal of Geophysical Research*, 115, B09204. <https://doi.org/10.1029/2009JB006975>
- Scott, H. P., Huggins, S., Frank, M. R., Maglio, S. J., Martin, C. D., Meng, Y., et al. (2007). Equation of state and high-pressure stability of Fe₃P-schreibersite: Implications for phosphorus storage in planetary cores. *Geophysical Research Letters*, 34, L06302. <https://doi.org/10.1029/2006GL029160>
- Seagle, C. T., Campbell, A. J., Heinz, D. L., Shen, G., & Prakapenka, V. B. (2006). Thermal equation of state of Fe₃S and implications for sulfur in Earth's core. *Journal of Geophysical Research*, 111, B06209. <https://doi.org/10.1029/2005JB004091>
- Seto, Y., Nishio-Hamane, D., Nagai, T., & Sata, N. (2010). Development of a software suite on X-ray diffraction experiments. *The Review of High Pressure Science and Technology*, 20(3), 269–276. <https://doi.org/10.4131/jshpreview.20.269>
- Shahar, A., Schauble, E. A., Caracas, R., Gleason, A. E., Reagan, M. M., Xiao, Y., et al. (2016). Pressure-dependent isotopic composition of iron alloys. *Science*, 352(6285), 580–582. <https://doi.org/10.1126/science.aad9945>
- Shen, G., Lin, J. F., Fei, Y., Mao, H. K., Hu, M., & Chow, P. (2003). Magnetic and structural transition in Fe₃S at high pressures. *Eos Transactions of American Geophysical Union*, 84(46), F1548–F1549.
- Shi, Y.-J., Du, Y.-L., & Chen, G. (2013). First-principles study on the elastic and electronic properties of hexagonal ϵ -Fe₃N. *Computational Materials Science*, 67, 341–345. <https://doi.org/10.1016/j.commatsci.2012.09.012>
- Sifkovits, M., Smolinski, H., Hellwig, S., & Weber, W. (1999). Interplay of chemical bonding and magnetism in Fe₄N, Fe₃N and zeta-Fe₂N. *Journal of Magnetism and Magnetic Materials*, 204(3), 191–198. [https://doi.org/10.1016/S0304-8853\(99\)00296-6](https://doi.org/10.1016/S0304-8853(99)00296-6)
- Stevenson, D. J. (2001). Mars' core and magnetism. *Nature*, 412(6843), 214–219. <https://doi.org/10.1038/35084155>
- Takemura, K., & Dewaele, A. (2008). Isothermal equation of state for gold with a He-pressure medium. *Physical Review B*, 78(10). <https://doi.org/10.1103/PhysRevB.78.104119>
- Toby, B. H. (2001). EXPGUI, a graphical user interface for GSAS. *Journal of Applied Crystallography*, 34(2), 210–213. <https://doi.org/10.1107/S0021889801002242>
- Vocadlo, L., Brodholt, J., Dobson, D. P., Knight, K. S., Marshall, W. G., Price, G. D., & Wood, I. G. (2002). The effect of ferromagnetism on the equation of state of Fe₃C studied by first-principles calculations. *Earth and Planetary Science Letters*, 203(1), 567–575. [https://doi.org/10.1016/S0012-821x\(02\)00839-7](https://doi.org/10.1016/S0012-821x(02)00839-7)
- Wetzel, M. H., Schwarz, M. R., & Leineweber, A. (2019). High-pressure high-temperature study of the pressure induced decomposition of the iron nitride γ' -Fe₄N. *Journal of Alloys and Compounds*. <https://doi.org/10.1016/j.jallcom.2019.06.078>
- Widenmeyer, M., Hansen, T. C., Meissner, E., & Niewa, R. (2014). Formation and decomposition of iron nitrides observed by in situ powder neutron diffraction and thermal analysis. *Zeitschrift für Anorganische und Allgemeine Chemie*, 640(7), 1265–1274. <https://doi.org/10.1002/zaac.201300676>
- Wriedt, H., Gokcen, N., & Nafziger, R. (1987). The Fe-N (iron-nitrogen) system. *Bulletin of Alloy Phase Diagrams*, 8(4), 355–377.
- Yoder, C. F., Konopliv, A. S., Yuan, D. N., Standish, E. M., & Folkner, W. M. (2003). Fluid core size of Mars from detection of the solar tide. *Science*, 300(5617), 299–303. <https://doi.org/10.1126/science.1079645>
- Zedgenizov, D. A., & Litasov, K. D. (2017). Looking for “missing” nitrogen in the deep Earth. *American Mineralogist*, 102(9), 1769–1770.
- Zhang, W. H., Lv, Z. Q., Shi, Z. P., Sun, S. H., Wang, Z. H., & Fu, W. T. (2012). Electronic, magnetic and elastic properties of ϵ -phases Fe₃X (X = B, C, N) from density-functional theory calculations. *Journal of Magnetism and Magnetic Materials*, 324(14), 2271–2276. <https://doi.org/10.1016/j.jmmm.2012.02.114>

References From the Supporting Information

- Dziewonski, A. M., & Anderson, D. L. (1981). Preliminary reference earth model. *Physics of the Earth and Planetary Interiors*, 25(4), 297–356. [https://doi.org/10.1016/0031-9201\(81\)90046-7](https://doi.org/10.1016/0031-9201(81)90046-7)
- Nakajima, Y., Takahashi, E., Sata, N., Nishihara, Y., Hirose, K., Funakoshi, K., & Ohishi, Y. (2011). Thermoelastic property and high-pressure stability of Fe₇C₃: Implication for iron-carbide in the Earth's core. *American Mineralogist*, 96(7), 1158–1165. <https://doi.org/10.2138/am.2011.3703>
- Sakai, T., Takahashi, S., Nishitani, N., Mashino, I., Ohtani, E., & Hirao, N. (2014). Equation of state of pure iron and Fe_{0.9}Ni_{0.1} alloy up to 3 Mbar. *Physics of the Earth and Planetary Interiors*, 228, 114–126. <https://doi.org/10.1016/j.pepi.2013.12.010>
- Thompson, S., Komabayashi, T., Breton, H., Suehiro, S., Glazyrin, K., Pakhomova, A., & Ohishi, Y. (2020). Compression experiments to 126 GPa and 2500 K and thermal equation of state of Fe₃S: Implications for sulphur in the Earth's core. *Earth and Planetary Science Letters*, 534. <https://doi.org/10.1016/j.epsl.2020.116080>