

Pressure-induced irreversible volume collapse in a high-entropy alloy

Raimundas Sereika ¹, Caleb M. Knight ¹, Kallol Chakrabarty ¹, Andrew D. Pope ¹,
Dean Smith ², and Yogesh K. Vohra ¹

¹*Department of Physics, University of Alabama at Birmingham, Birmingham, Alabama 35294, USA*

²*HPCAT, X-ray Science Division, Argonne National Laboratory, Lemont, Illinois 60439, USA*



(Received 1 April 2025; accepted 1 July 2025; published 24 July 2025)

At ambient conditions, the high-entropy alloy superconductor $\text{Re}_{0.6}(\text{NbTiZrHf})_{0.4}$ exhibits exceptional mechanical properties among high-entropy alloys, with its hexagonal phase achieving nanoindentation hardness of 18.5 GPa. We report on a unique pressure-induced structural transformation from a hexagonal phase to a body-centered cubic (BCC) phase, revealed by synchrotron x-ray diffraction measurements up to 70 GPa. This first-order transition, accompanied by a 6.1% volume collapse, occurs at 44 GPa and results in a BCC structure with random site occupancy by the five constituent elements, which is remarkably retained upon decompression to ambient conditions. The transformation proceeds via a martensiticlike, diffusionless mechanism without elemental segregation, enabled by pressure-induced electronic redistribution and atomic-scale disorder. These findings demonstrate a rare case of metastable phase retention in a chemically complex alloy and offer new insights into structure-stability relationships under pressure.

DOI: [10.1103/zsmk-3vnt](https://doi.org/10.1103/zsmk-3vnt)

I. INTRODUCTION

High-entropy alloys (HEAs) have attracted significant interest due to their unconventional phase stability, mechanical robustness, and superconducting properties [1–5]. The stability of these materials arises from configurational entropy—the thermodynamic dominance of disordered atomic arrangements—which drives unique structural responses under extreme stimuli such as pressure. Specifically, pressure-induced phase transitions in HEAs are of particular interest, as they provide valuable insights into lattice dynamics and their structural integrity, yet many questions remain regarding the underlying mechanisms that govern these transformations.

Here, we report an unusual pressure-induced hexagonal to body-centered cubic (BCC) transition in the high-entropy superconductor $\text{Re}_{0.6}(\text{NbTiZrHf})_{0.4}$ (atomic distribution $\text{Re}_{0.6}\text{Nb}_{0.1}\text{Ti}_{0.1}\text{Zr}_{0.1}\text{Hf}_{0.1}$). This transformation is unusual for three main reasons: (i) application of high-pressure typically favors the formation of close-packed structures, such as previously observed FCC-to-HCP, BCC-to-HCP, and HCP-to-distorted phases in various HEAs, often governed by a balance between enthalpy, atomic size effects, and electronic structure considerations [3,4]; (ii) several compositionally similar HEAs exhibit structural stability under high pressures without any phase transitions. For instance, $(\text{TaNb})_{0.67}(\text{HfZrTi})_{0.33}$ crystallizes in a BCC structure that remains stable up to at least 96 GPa without structural changes [5], and its superconducting state persists at pressures as high as 190 GPa; (iii) pure rhenium, a key constituent of our alloy, retains

hexagonal symmetry without undergoing any structural transition under extreme pressures [6,7].

The discovery of a hexagonal-to-BCC transition in $\text{Re}_{0.6}(\text{NbTiZrHf})_{0.4}$, despite these stability trends, suggests that a combination of chemical disorder, lattice distortions, and kinetic barriers unique to high-entropy alloys governs the transition. Upon decompression, the BCC phase remains trapped, exhibiting metastability rather than reverting to the hexagonal phase. Such unexpected retention challenges conventional thermodynamic expectations and suggests a pathway for pressure-tuned phase engineering. Therefore, in this paper, we focus on characterizing this unexpected hexagonal-to-BCC transition and the retention of the BCC phase upon decompression.

II. MATERIALS AND METHODS

$\text{Re}_{0.6}(\text{NbTiZrHf})_{0.4}$ was synthesized by arc melting high-purity elemental metals (all with purities of $\geq 99.95\%$) in their prescribed ratios under an argon atmosphere, using a compact arc melter MAM-1 (Edmund Bühler GmbH, Bodelshausen, Germany). To ensure chemical homogeneity, the ingot was flipped and remelted several times. Scanning electron microscopy with energy-dispersive x-ray spectroscopy (SEM-EDS) was performed using a Quanta FEG 650 microscope to examine the sample composition and surface morphology. All SEM-EDS analyses were conducted at ambient pressure and room temperature, first on the as-synthesized bulk sample and then on the sample recovered after the high-pressure x-ray diffraction experiments. Using typical operating parameters, such as an accelerating voltage of 20 kV, the interaction volume of the electron beam with the metallic sample results in an x-ray generation depth of approximately 2–5 μm . This ensures that the compositional information obtained is representative of a substantial near-surface region rather than

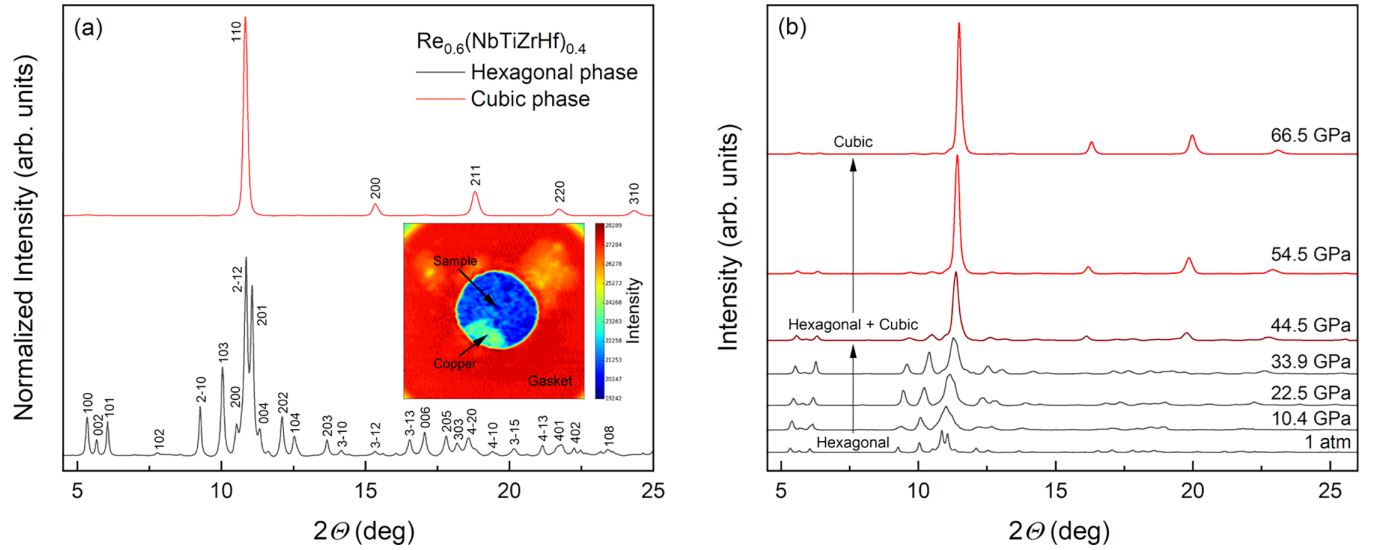


FIG. 1. (a) Comparison of XRD patterns at ambient conditions for the initial hexagonal phase (black) and the BCC phase (red), which was stabilized under high pressure and retained upon decompression. (b) Evolution of powder diffraction patterns during compression, showing gradual transformation from the hexagonal phase to the cubic phase. The background has been subtracted for clarity. The inset presents a 2D x-ray transmission map of the sample chamber, showing the distribution of $\text{Re}_{0.6}(\text{NbTiZrHf})_{0.4}$ powders (blue) and copper (cyan) within the stainless-steel gasket (red), where the color scale represents the transmitted x-ray intensity.

being strictly surface limited. To verify the phase purity and confirm successful synthesis, laboratory x-ray diffraction was performed under ambient conditions using a PANalytical Empyrean diffractometer equipped with $\text{Cu-K}\alpha$ radiation. The diffraction pattern indicates that the sample adopts a single-phase structure consistent with the hexagonal symmetry of the $P6_3/mmc$ space group (No. 194). The refined lattice parameters, $a = b = 5.257(5)$ Å and $c = 8.6148(5)$ Å, closely match those reported for a compositionally similar alloy, $\text{Re}_{0.56}(\text{NbTiZrHf})_{0.44}$ [8]. To evaluate the mechanical hardness, nanoindentation experiments were carried out using an Agilent Nano Indenter G200 equipped with a Berkovich diamond tip (nominal radius: 50 nm) and operated in continuous stiffness measurement mode. Calibration was performed before and after each measurement using a fused silica reference standard (Young's modulus = 72 ± 3 GPa). The consistent values obtained from the reference confirmed the stability of the tip geometry throughout testing. Following synthesis and ambient characterization, we present high-pressure x-ray diffraction results to track structural evolution under compression. We then correlate these findings with mechanical property measurements and elemental distribution analysis, finalizing in a discussion of the potential mechanism driving the irreversible transition.

High-pressure x-ray diffraction (XRD) experiments were conducted at beamline 16-ID-B of HPCAT, Advanced Photon Source (Argonne National Laboratory), using *in situ* synchrotron angular-dispersive x-ray diffraction. Powdered $\text{Re}_{0.6}(\text{NbTiZrHf})_{0.4}$ was loaded into diamond anvil cells (DACs) equipped with 250 μm culets and compressed from ambient pressure up to 70 GPa. A stainless-steel gasket, precompressed to 38 μm , was drilled to 80 μm in diameter to form a sample chamber, which also contained a copper pressure marker [see insert of Fig. 1(a)]. A monochromatic x-ray beam with a wavelength of 0.4246 Å was used to

collect diffraction data. The resulting 2D diffraction images were integrated using DIOPTAS [9], crystallographic parameters were refined using JANA2020 [10], and the pressure-volume data were analyzed by fitting to a third-order Birch-Murnaghan equation of state using EoSFit [11].

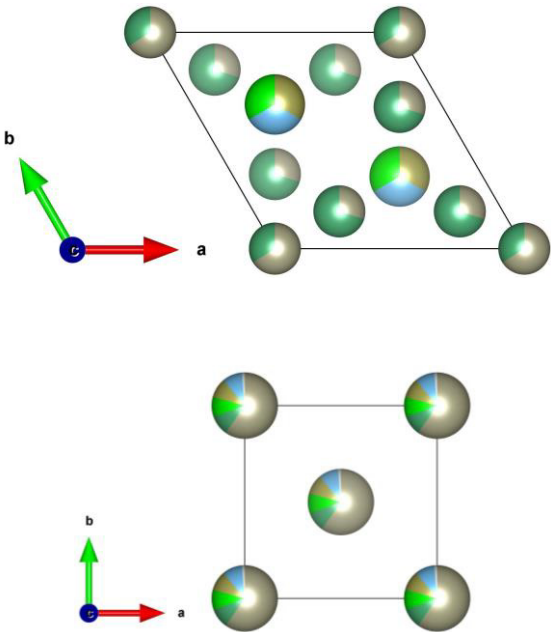
III. RESULTS AND DISCUSSION

Figure 1(a) shows $\text{Re}_{0.6}(\text{NbTiZrHf})_{0.4}$ in its original ambient-pressure hexagonal phase, alongside the pressure-induced BCC phase that remains after decompression (for detailed crystallographic information, see Table I). Upon increasing pressure, a structural transformation from hexagonal-to-BCC begins near 44 GPa, as evidenced by a reduction in the number of diffraction peaks and marked changes in peak intensities [Fig. 1(b)]. Once the transformation is complete, the sample adopts a fully BCC structure. As noted above, the BCC phase is remarkably retained after decompression to ambient pressure, exhibiting clear metastability and confirming irreversible trapping of the high-pressure phase. While pressure-induced phases in solids often revert (fully or partially) to their original structures upon decompression, complete retention is relatively rare in metallic systems. To confirm this transition, we prepared an additional sample and repeated the measurements under identical conditions. Both experimental runs were refined using the Le Bail method, and the pressure dependence of the unit-cell volume was extracted. As shown in Fig. 2, the volume decreases monotonically with pressure but displays a clear discontinuity at the transition, with a relative volume change of $\Delta V/V \approx 5.7\text{--}6.1\%$, consistent with a first-order phase transition. A slight offset between the BCC data collected during compression and decompression is observed, which likely arises from experimental factors such as grain reorientation, pressure gradients, or subtle differences in sample

TABLE I. Crystallographic information for the $\text{Re}_{0.6}\text{Nb}_{0.1}\text{Ti}_{0.1}\text{Zr}_{0.1}\text{Hf}_{0.1}$ structure in the hexagonal ($P6_3/mmc$, No. 194) and cubic ($Im\bar{3}m$, No. 229) phases at ambient conditions. The cubic phase adopts a disordered BCC structure with random occupation of the 2a and 2b Wyckoff sites by all five elements. No superlattice reflections were observed in x-ray diffraction, confirming the absence of B2-type ordering.

Hexagonal $P6_3/mmc$ (no. 194), $\alpha = \beta = 90^\circ, \gamma = 120^\circ$.				
$a = b = 5.257(5) \text{ \AA}, c = 8.6148(5) \text{ \AA}, V = 206.22 \text{ \AA}^3$.				
Atom	X	y	z	Site
Re/Nb	0.00000	0.00000	0.00000	2a
Re/Nb	0.17233	0.34466	1/4	6h
Ti/Zr/Hf	2/3	1/3	0.06387	4f

Cubic $Im\bar{3}m$ (no. 229), $\alpha = \beta = \gamma = 90^\circ$.				
$a = b = c = 3.188(5) \text{ \AA}, V = 32.42 \text{ \AA}^3$.				
Atom	x	Y	z	Site
Re/Nb/Ti/Zr/Hf	1/2	1/2	1/2	2a
Re/Nb/Ti/Zr/Hf	0.00000	0.00000	0.00000	2b



alignment within the DAC. While the BCC structure is typically less densely packed than HCP in ideal hard-sphere models, in this chemically disordered alloy under compression, the BCC phase becomes denser. This counterintuitive densification arises from pressure-induced electronic redis-

tribution, nonuniform atomic compressibility, and relaxation of local distortions inherent to the HCP phase. The result is a more compact BCC configuration, as evidenced by the volume collapse. Importantly, repeated measurements confirm that the equation of state behavior is reproducible, with consistent P - V trends across both experimental runs.

Fitting the pressure-volume data to a third-order Birch-Murnaghan equation of state reveals distinct elastic behaviors for the hexagonal and BCC phases (Fig. 2 and Table II in the Appendix). The hexagonal phase exhibits a bulk modulus (elastic stiffness) of $B_0 \approx 261 - 277 \text{ GPa}$, indicating relatively low compressibility. Nanoindentation measurements further demonstrate a high mechanical hardness of 18.5 GPa, significantly greater than the hardness reported for pure rhenium ($\sim 12\text{--}15 \text{ GPa}$). Despite this high hardness, the alloy's bulk modulus is lower than that of elemental Re ($B_0 \approx 360 \text{ GPa}$ [6]). This apparent contradiction arises because hardness measures resistance to localized plastic deformation, while the bulk modulus quantifies resistance to uniform volumetric compression. The lower bulk modulus of the alloy relative to pure Re suggests that chemical disorder and configurational entropy disrupt long-range atomic coherence, reducing resistance to volumetric compression while preserving strong short-range bonding, thereby maintaining high mechanical hardness. Full nanoindentation data, including load-displacement curves and depth-dependent mechanical property profiles, are provided in Fig. 3.

Our observations indicate that the hexagonal-to-BCC transition in $\text{Re}_{0.6}(\text{NbTiZrHf})_{0.4}$ proceeds via a diffusionless, martensiticlike mechanism [12–14]. As pressure increases, the transformation initiates with the nucleation of BCC regions within the hexagonal matrix. These regions grow

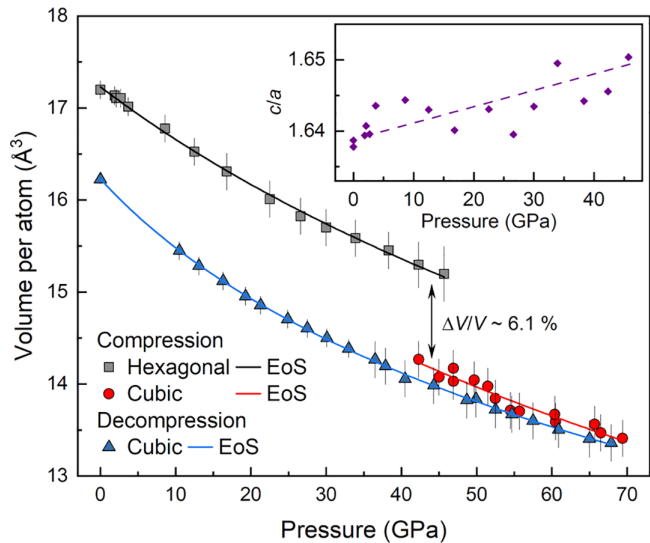


FIG. 2. Pressure-dependent volume evolution of $\text{Re}_{0.6}(\text{NbTiZrHf})_{0.4}$, showing the behavior of the hexagonal phase (before transition) and the cubic phase (after transition). The solid lines represent third-order Birch-Murnaghan EoS fits to the experimental data. The inset depicts the variation of the unit-cell axial ratio (c/a) with pressure in the hexagonal phase, where the dashed line is included as a visual guide.

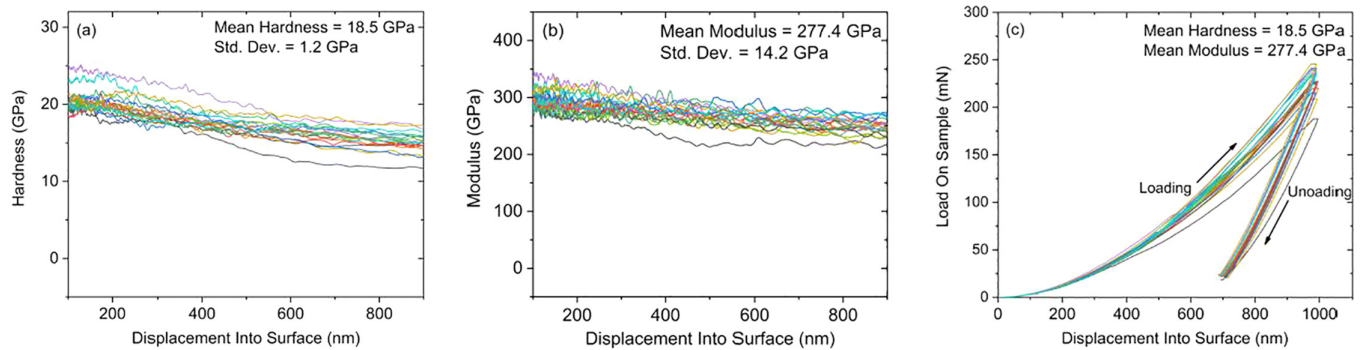


FIG. 3. Nanoindentation results for the high-entropy alloy $\text{Re}_{0.6}(\text{NbTiZrHf})_{0.4}$. (a) Hardness as a function of indentation depth, showing a mean hardness of 18.5 GPa. (b) Elastic modulus as a function of indentation depth, yielding a mean modulus of 277.4 GPa. (c) Load-displacement curves from multiple indentations, indicating consistent mechanical response across measurements.

cooperatively through shearlike atomic displacements, gradually consuming the parent phase without requiring long-range atomic diffusion. This displacive mechanism is directly supported by three key points:

The transition exhibits an abrupt, discontinuous volume collapse ($\sim 6.1\%$) near 44 GPa (Fig. 2), consistent with a first-order displacive transformation. Such a sharp change in volume per atom indicates a sudden structural reconfiguration, characteristic of coordinated atomic shear rather than gradual diffusion [13,14].

The absence of intermediate crystalline phases in synchrotron XRD data [Fig. 1(b)] confirms a direct transition pathway. Diffusive transformations often involve transient phases (e.g., dhcp or distorted intermediates), whereas the clean coexistence of only hexagonal and BCC phases supports a shear-dominated mechanism [3].

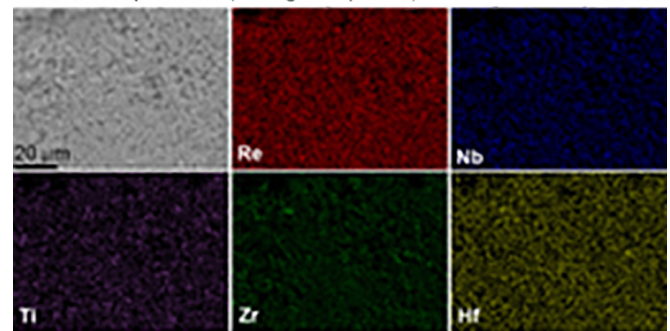
The hexagonal-to-BCC transition shows volume discontinuity, however, there is a range of pressures in the XRD data where these two phases coexist (Fig. 2). While minor pressure gradients in the DAC may contribute to coexistence, the HEA's intrinsic disorder dominates this behavior, as evidenced by reproducibility across experimental runs (Fig. 6 in the Appendix).

Further evidence supporting a nondiffusive mechanism is provided by SEM-EDS elemental mapping (Fig. 4). Analyses performed at ambient conditions, both before pressure application and after recovery from nearly 70 GPa, show no signs of elemental segregation, phase separation, or grain boundary enrichment. The distributions of Re, Nb, Ti, Zr, and Hf remain spatially uniform across the scanned areas, confirming that the chemical homogeneity is preserved during compression and decompression. While SEM-EDS primarily probes near-surface regions, the persistence of chemical uniformity throughout the sample is further supported by synchrotron XRD results. The diffraction patterns (Fig. 1 and Fig. 7 in the Appendix), which probe the bulk sample volume, show clean reflections from both the initial hexagonal and retained BCC phases, with no evidence of secondary phases, chemical demixing, or significant peak broadening indicative of inhomogeneity or major defect formation.

Concerns regarding potential elemental rearrangement during or after decompression—resulting in a superficially uniform state—are mitigated by kinetic considerations. The experiments were performed at room temperature, with

pressure released over several minutes. Under these conditions, atomic diffusion in metallic systems, especially in chemically complex HEAs, is exceedingly slow. The limited thermal energy and short timescale provide insufficient

Before compression (hexagonal phase)



After compression (cubic phase)

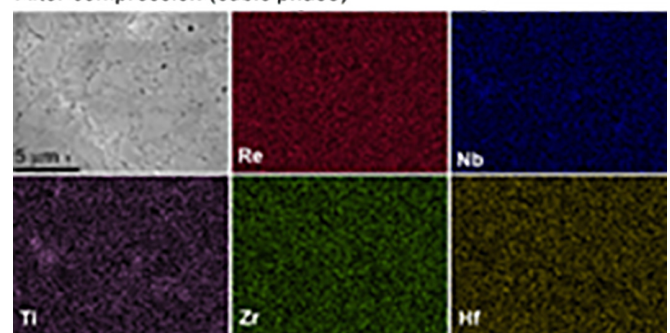


FIG. 4. Elemental distribution maps of $\text{Re}_{0.6}(\text{NbTiZrHf})_{0.4}$ collected by SEM-EDS before (top) and after (bottom) high-pressure compression. Each panel displays the spatial distribution of a specific constituent element (Re, Nb, Ti, Zr, or Hf, as labeled). The color intensity within each map corresponds to the local relative concentration of that element; brighter areas indicate higher relative abundance. The difference in image scale bars (20 μm for "before compression," 5 μm for "after compression") is a consequence of the significantly smaller sample area accessible for analysis after its recovery from the confines of the diamond anvil cell gasket. Despite the change in magnification, the maps demonstrate a maintained uniform elemental distribution—meaning no significant spatial variation in elemental composition, clustering, or measurable segregation—across the analyzed areas in both the initial and recovered states.

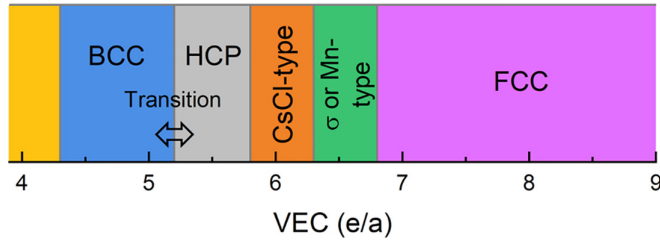


FIG. 5. Schematic diagram showing the correlation between valence electron concentration (VEC, in e^-/atom) and preferred crystal structure in superconducting high-entropy alloys. The diagram illustrates regions of stability for BCC, HCP, FCC, and complex intermetallic structures. Adapted from [20,21].

kinetic driving force for long-range elemental redistribution. Moreover, the retention of the high-pressure BCC phase at ambient conditions [Fig. 1(a)], rather than reversion to the equilibrium hexagonal phase, signifies that the atomic configuration is kinetically trapped. This trapping would similarly inhibit any substantial diffusion-driven compositional rearrangement upon depressurization. Therefore, the observed chemical uniformity is interpreted as representative of the sample throughout the pressure-induced transformation, consistent with a diffusionless, martensiticlike mechanism. Such transformations preserve chemical homogeneity by proceeding through coordinated atomic displacements rather than long-range diffusion, thereby maintaining the high configurational entropy characteristic of the HEA solid solution [15].

Beyond structural and mechanical factors, electronic effects play a significant role in the observed phase transition. In compositionally tuned HEAs, increasing the valence electron concentration (VEC)—defined as the average number of valence electrons per atom—strongly correlates with structural preferences. For instance, increasing VEC via alloying typically promotes a structural transition from BCC to HCP. In the $[\text{Nb}_{0.67-x}\text{Re}_x][\text{TiZrHf}]_{0.33}$ system, adding rhenium (which increases VEC) induces a BCC-to-HCP transformation starting around a VEC of 5.2, reaching a pure HCP phase at $x = 0.56$ (VEC ≈ 5.79) [8]. Comparable VEC-driven effects occur in other Re-rich HEAs, such as $\text{Re}_x(\text{HfTaWIr})_{1-x}$ and $\text{Re}_x(\text{HfTaWPt})_{1-x}$ [16]. These composition-based trends are schematically illustrated in Fig. 5, mapping broad stability regions for BCC, HCP, FCC, and more complex structures across different VEC values in superconducting HEAs. Our alloy, $\text{Re}_{0.6}(\text{NbTiZrHf})_{0.4}$, has a calculated VEC of 5.9, placing it firmly within the hexagonal stability region at ambient pressure.

To elucidate the electronic basis for this phase transition, we propose the following two arguments for theoretical considerations. The first argument is that enhanced overlap of metal d orbitals broadens the valence bands and redistributes electron density near the Fermi level. This pressure-induced hybridization weakens the directional bonding that stabilizes the hexagonal structure, thereby directly promoting the formation of the cubic BCC lattice. The inset of Fig. 2 shows a slight increase in the axial ratio (c/a) of the hexagonal phase under pressure. This minimal variation likely reflects elastic anisotropy rather than a significant change in the bonding character. While it does not directly indicate

enhanced orbital overlap, it is consistent with a relatively undistorted hexagonal lattice accommodating gradual electronic structure evolution under compression. Although the BCC structure has higher crystallographic symmetry, its lower atomic coordination number relative to the hexagonal phase means it is not inherently more isotropic in terms of atomic packing. Nevertheless, the electronic symmetry and modified orbital overlap in the BCC structure under pressure may yield a more energetically favorable electronic configuration, thereby driving the observed structural transition.

The second argument is built on changes in VEC under pressure. The nominal valence electron concentration (VEC) remains fixed, and the pressure-induced broadening and shifts in electronic bands effectively modify electron filling conditions, energetically stabilizing the BCC structure over the original hexagonal phase. This interpretation aligns with Pettifor's band-energy model [17–19], where partially filled d bands at electron counts similar to ours can exhibit lower electronic energy in the BCC configuration than in HCP or FCC structures. In other words, pressure-driven band broadening effectively shifts the alloy into an electronic regime where the BCC structure is energetically favored. This concept parallels prior studies linking effective electronic structure to crystal symmetry in superconducting HEAs [20,21]. Thus, the observed hexagonal-to-cubic transition can be viewed as a pressure-driven, diffusionless shear transformation stabilized by electronically redistributed states.

Upon decompression, the BCC phase does not revert to the original hexagonal structure, indicating that the high-pressure configuration is kinetically trapped. Retention of this metastable BCC structure is attributed to kinetic factors such as the absence of a facile diffusive pathway, a significant energy barrier to reverse martensitic transformation, and the intrinsic chemical disorder of the HEA, which inhibits atomic rearrangements. Moreover, the pressure-induced electronic configuration likely continues to energetically favor the BCC lattice at ambient conditions. Collectively, these electronic and kinetic factors explain the persistence of the BCC structure despite the fixed VEC.

IV. CONCLUSIONS

In summary, we report a pressure-induced hexagonal-to-cubic transformation in $\text{Re}_{0.6}(\text{NbTiZrHf})_{0.4}$ via a martensiticlike, diffusionless mechanism strongly influenced by electronic structure evolution. After decompression, the BCC phase is retained in a metastable form at ambient pressure as the dominant structure. SEM-EDS analysis before and after compression shows uniform elemental distribution, consistent with a nondiffusive transformation pathway. The differing bulk moduli of the hexagonal and cubic phases indicate that mechanical properties strongly depend on crystal structure, which may also impact superconducting behavior—an intriguing area for further investigation. Overall, these findings highlight how valence electron count, bonding anisotropy, and configurational disorder collectively govern phase stability and mechanical behavior in complex alloys subjected to extreme conditions.

ACKNOWLEDGMENTS

This material is based upon work supported by the National Science Foundation (NSF) under Grant No. DMR-2310526. Portion of this work was performed at the HPCAT (Sector 16), Advanced Photon Source (APS), Argonne National Laboratory. HPCAT operations are supported by DOE-NNSA's Office of Experimental Sciences. The Advanced Photon Source is 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.

DATA AVAILABILITY

The data that support the findings of this article are not publicly available upon publication because it is not technically feasible and/or the cost of preparing, depositing, and hosting the data would be prohibitive within the terms of this research project. The data are available from the authors upon reasonable request.

APPENDIX

TABLE II. The bulk modulus (B_0) and its pressure derivative (B'_0) were extracted from third-order Birch-Murnaghan equation-of-state fits to pressure-volume data obtained during two independent experimental runs. Results are provided for the ambient phase during initial compression, the high-pressure phase, and the retained phase after decompression.

Phase	Pressure range	B_0 (GPa)	B'_0
Hexagonal (run 1)	Compression from 1 bar to 44.5 GPa	261.2 ± 1	2.6
Hexagonal (run 2)	Compression from 1 bar to 45.7 GPa	276.8 ± 1.2	4.0
Cubic (run1)	Compression from 41.7 to 69.1 GPa	369.4 ± 0.5	4.0
Cubic (run 2)	Compression from 42.3 to 69.4 GPa	366.4 ± 0.8	4.0
Cubic (run 1)	Decompression from 69.1 GPa to 1 bar	181.7 ± 0.2	8.8
Cubic (run 2)	Decompression from 67.9 GPa to 1 bar	180.5 ± 0.2	6.8

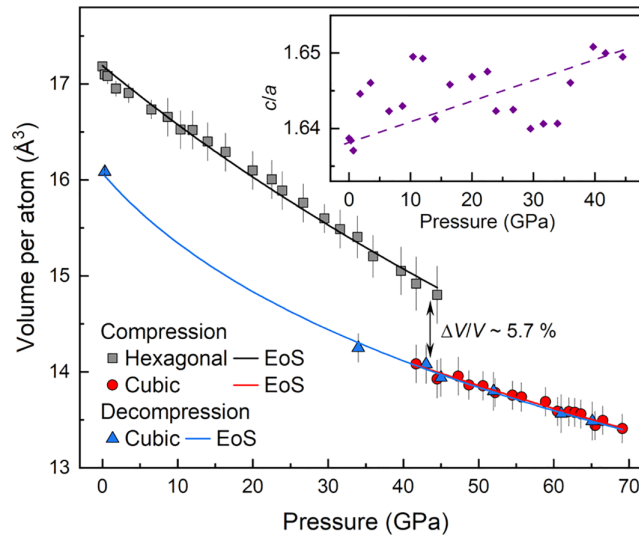


FIG. 6. Pressure-dependent volume evolution of $\text{Re}_{0.6}(\text{NbTiZrHf})_{0.4}$, showing the behavior of the hexagonal phase (before transition) and the cubic phase (after transition) in repeated experiments (Run 1). The solid lines represent third-order Birch-Murnaghan EoS fits to the experimental data. The inset depicts the variation of the unit-cell axial ratio (c/a) with pressure in the hexagonal phase, where the dashed line is included as a visual guide.

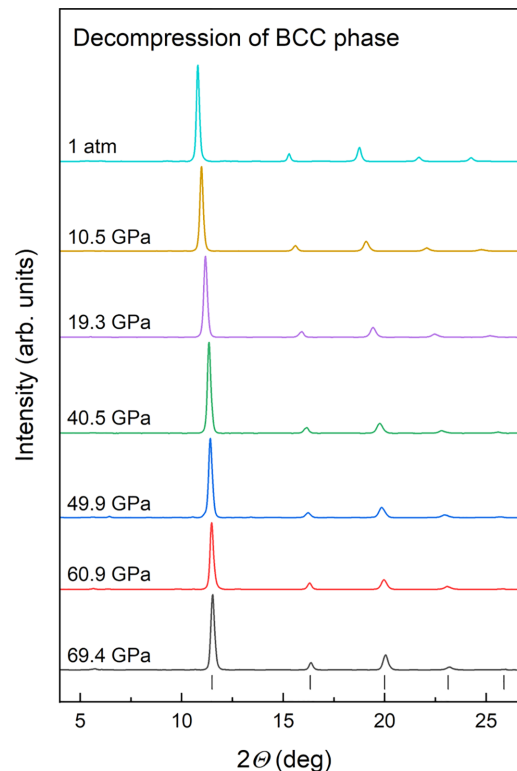


FIG. 7. Evolution of powder x-ray diffraction patterns during decompression from nearly 70 GPa to ambient pressure. The positions of the initial BCC Bragg reflections at 69.4 GPa are marked by vertical bars.

- [1] E. P. George, D. Raabe, and R. O. Ritchie, High-entropy alloys, *Nat. Rev. Mater.* **4**, 515 (2019).
- [2] X. Chang, M. Zeng, K. Liu, and L. Fu, Phase engineering of high-entropy alloys, *Adv. Mater.* **32**, 1907226 (2020).
- [3] F. Zhang, H. Lou, B. Cheng, Z. Zeng, and Q. Zeng, High-pressure induced phase transitions in high-entropy alloys: A review, *Entropy* **21**, 239 (2019).
- [4] C. L. Tracy, S. Park, D. R. Rittman, S. J. Zinkle, H. Bei, M. Lang, R. C. Ewing, and W. L. Mao, High pressure synthesis of a hexagonal close-packed phase of the high-entropy alloy CrMnFeCoNi, *Nat. Commun.* **8**, 15634 (2017).
- [5] J. Guo, H. Wang, F. von Rohr, Z. Wang, S. Cai, Y. Zhou, K. Yang, A. Li, S. Jiang, Q. Wu, R. J. Cava, and L. Sun, Robust zero resistance in a superconducting high-entropy alloy at pressures up to 190 GPa, *Proc. Natl Acad. Sci. USA* **114**, 13144 (2017).
- [6] L. Dubrovinsky, N. Dubrovinskaia, V. B. Prakapenka, and A. M. Abakumov, Implementation of micro-ball nanodiamond anvils for high-pressure studies above 6 Mbar, *Nat. Commun.* **3**, 1163 (2012).
- [7] G. L. Rech, J. E. Zorzi, and C. A. Perottoni, Equation of state of hexagonal-close-packed rhenium in the terapascal regime, *Phys. Rev. B* **100**, 174107 (2019).
- [8] S. Marik, K. Motla, M. Varghese, K. P. Sajilesh, D. Singh, Y. Breard, P. Boullay, and R. P. Singh, Superconductivity in a new hexagonal high-entropy alloy, *Phys. Rev. Mater.* **3**, 060602(R) (2019).
- [9] C. Prescher and V. B. Prakapenka, DIOPTAS: A program for reduction of two-dimensional x-ray diffraction data and data exploration, *High Press. Res.* **35**, 223 (2015).
- [10] V. Petricek, L. Palatinus, J. Plasil, and N. Dusek, Jana2020—a new version of the crystallographic computing system jana, *Z. Kristallogr.* **238**, 271 (2023).
- [11] R. J. Angel, M. Alvaro, and J. Gonzalez-Platas, EosFit7c and a Fortran module (library) for equation of state calculations, *Z. Kristallogr. - Cryst. Mater.* **229**, 405 (2014).
- [12] C. M. Wayman, *Introduction to the Crystallography of Martensitic Transformations* (Macmillan, New York, 1964).
- [13] K. Otsuka and X. Ren, Physical metallurgy of Ti–Ni-based shape memory alloys, *Prog. Mater. Sci.* **50**, 511 (2005).
- [14] J. W. Christian and S. Mahajan, Deformation twinning, *Prog. Mater. Sci.* **39**, 1 (1995).
- [15] D. B. Miracle and O. N. Senkov, A critical review of high entropy alloys and related concepts, *Acta Mater.* **122**, 448 (2017).
- [16] K. Stolze, F. A. Cevallos, T. Kong, and R. J. Cava, High-entropy alloy superconductors on an α -Mn lattice, *J. Mater. Chem. C* **6**, 10441 (2018).
- [17] D. G. Pettifor, A chemical scale for crystal-structure maps, *Solid State Commun.* **51**, 31 (1984).
- [18] D. G. Pettifor, The structures of binary compounds. I. Phenomenological structure maps, *J. Phys. C Solid State Phys.* **19**, 285 (1986).
- [19] D. G. Pettifor, *Bonding and Structure of Molecules and Solids* (Oxford University Press, Oxford, 1995).

- [20] L. Sun and R. J. Cava, High-entropy alloy superconductors: Status, opportunities, and challenges, [Phys. Rev. Mater. **3**, 090301 \(2019\)](#).
- [21] D. Strong and R. J. Cava, Superconductivity in the face-centered cubic W-M-Rh-Ir-Pt $M = \{\text{Mo}, \text{Nb}, \text{Ta}, \text{Re}\}$ high-entropy alloy, [J. Mater. Sci. **59**, 10347 \(2024\)](#).