

Exploring high pressure structural transformations, electronic properties and superconducting properties of $M\text{H}_2$ ($M = \text{Nb}, \text{Ta}$)

Jinquan Zhang^a, Yanqi Wang^a, Libiao Tang^a, Juyi Duan^a, Jingjing Wang^b, Song Li^a, Meng Ju^c, Weiguo Sun^d,
Yuanyuan Jin^{a,*}, Chuanzhao Zhang^{a,*}

^aDepartment of Physics and Optoelectronic Engineering, Yangtze University, Jingzhou 434023, China

^bCollege of Computer and Information Engineering, Hubei Normal University, Huangshi 435002, China

^cSchool of Physical Science and Technology, Southwest University, Chongqing 400715, China

^dCollege of Physics and Electronic Information, Luoyang Normal University, Luoyang 471022, China

Abstract

The high-pressure structures and properties of $M\text{H}_2$ ($M = \text{Nb}, \text{Ta}$) are explored through an ab initio evolutionary algorithm for crystal structure prediction and first-principles calculations. It is found that NbH_2 undergoes a phase transition from a cubic $Fm\bar{3}m$ structure with regular NbH_8 cubes to an orthorhombic $Pnma$ structure with fascinating distorted NbH_9 tetrakaidecahedrons at 48.8 GPa, while the phase transition pressure of TaH_2 from a hexagonal $P6_3mc$ phase with slightly distorted TaH_7 decahedron to an orthorhombic $Pnma$ phase with attractive distorted TaH_9 tetrakaidecahedrons is about 90.0 GPa. Besides, the calculated electronic band structure and density of states demonstrate that all of these structures are metallic. The Poisson's ratio, electron localization function (ELF) and Bader charge analysis suggest that these phases possess dominant ionic bonding character with the effective charges transferring from the metal atom to H. From our electron-phonon calculations, the calculated superconducting critical temperature T_c of the $Pnma$ - NbH_2 is 6.903 K at 50 GPa. Finally, via the quasi-harmonic approximation method, the phase diagrams at pressure up to 300 GPa and temperature up to 1000 K of $M\text{H}_2$ ($M = \text{Nb}, \text{Ta}$) are established, where the transition pressure of $Fm\bar{3}m$ - $\text{NbH}_2 \rightarrow Pnma$ - NbH_2 and $P6_3mc$ - $\text{TaH}_2 \rightarrow Pnma$ - TaH_2 was found to decrease with increasing temperature.

Keywords: metal hydrides, first-principles calculation, high pressure, electron localization function, superconductivity, pressure-temperature phase diagram

1. Introduction

Metal hydrides, especially under high pressure, have attracted wide attention because of their unique physical properties and attractive applications, such as clean energy with the ability to replace fossil fuels as hydrogen storage materials and potential high-temperature superconductivity. For example, some hydrogen-rich compounds, including YH_6 , [1, 2] YH_9 , [3] CeH_9 , [4, 5] CeH_{10} , [6] ThH_9 , [7] ThH_{10} , [7] LaH_{10} , [8] SnH_{12} [9, 10], UH_7 , [11] and CaH_6 [12, 13] have been proved to have good superconductivity with high superconducting temperatures ranging from 44 to 262 K at high pressures and a hydrogen-rich compound rhodium trihydride (RhH_3) with a high volumetric hydrogen density of 212.5 g H_2/L could be used as a hydrogen storage material. [14]

In recent years, transition metal hydrides have also been extensively studied under high pressure, which can be summarized as the following two aspects. On the one hand, the late transition metals with higher and comparable electronegativity values (e.g., 2.2 for Ru, Pd, Os, and

Ir; 2.28 for Pt; 2.36 for W; 2.54 for Au) than that of hydrogen (2.2) are unfavorable react with hydrogen at ambient pressure. However, fortunately, high pressure can make the chemical potential of hydrogen rise sharply, thus effectively stimulating the chemical reactivity of elements, which makes the reaction between hydrogen and post-transition metals become a reality. [15] Previous high-pressure experiments have shown that high pressure makes it possible to synthesize Rh, Ir, and Pt hydrides. For example, a potential hydrogen source material rhodium dihydride RhH_2 [16] with a volume hydrogen density of 163.7 g H_2/L was discovered at room temperature at 8 GPa, and iridium trihydride IrH_3 [17] was successfully synthesized above 65 GPa at room temperature by in-situ X-ray diffraction measurement. Besides, PtH is a superconductor with $T_c = 10\text{--}25$ K at high pressure. [18] On the other hand, as for the early transition metals, although it is found that they are easy to form hydrides under environmental conditions, such as $\text{ScH}_2/\text{ScH}_3$, YH_2/YH_3 , TiH_2 , ZrH_2 , HfH_2 , VH_2 , and NbH_2 , after compression, some transition metal hydrides show attractive characteristics and undergo complex phase transitions that cannot be found under normal conditions. [19, 20, 21, 22, 23] For example, theoretical studies show that TiH_2 undergoes a

*Corresponding author

Email addresses: scujoyy@163.com (Yuanyuan Jin),
zcz19870517@163.com (Chuanzhao Zhang)

structural transition of $I4/mmm \rightarrow P4/nmm \rightarrow P2_1/m$ under high pressure at the corresponding transition pressures of 63 GPa and 294 GPa, respectively, and the phase transition from $I4/mmm$ to $P4/nmm$ at 63 GPa is more suitable for the experimental XRD pattern and the resulting unit cell parameters.[24, 25] A subsequent experiment on the structures and properties of ZrH_2 were also investigated under high pressure, which provided a new method for finding hydrogen structures with higher bulk density in transition metal hydrides without static pressure or shear stress.[26] Subsequently, the theoretical study of HfH_2 revealed that it undergoes pressure-induced structural phase transition $I4/mmm \rightarrow Cmma \rightarrow P2_1/m$ at 180 GPa and 250 GPa, respectively, and the T_c of $P2_1/m$ - HfH_2 at 260 GPa is 10.62–12.8 K.[27] Moreover, Ye *et al.* reported that the structural sequence of ScH_2 should be $Fm\bar{3}m \rightarrow C2/m$, with transformation pressures of 65 GPa.[28] Recent ab initio calculations predicted that $Fm\bar{3}m$ - ScH_2 [29] with T_c up to 38.11 K at 30 GPa is close to that of MgB_2 (39 K).[30, 31] This motivated us to find its new structures and explore the high-temperature superconductive property by compressing compounds of early transition metals with hydrogen.

With regard to group 5 element dihydrides, the high-pressure structures and related structural and electronic properties of VH_2 and NbH_2 have also been deeply explored under high pressure. The two groups predicted that VH_2 transforms from $Fm\bar{3}m$ structure to orthogonal $Pnma$ phase at about 50 GPa and the T_c estimate of two stable VH_2 structures is only several Kelvins.[32, 33] As for NbH_2 , Gao *et al.*[34, 35] report a phase transition sequence of $Fm\bar{3}m \rightarrow Pnma$ at 50 GPa. However, Chen *et al.* used an evolutionary algorithm to detect their stability in the pressure range of 0–100 GPa and found that the ground state $Fm\bar{3}m$ - NbH_2 transformed to $P6_3mc$ - NbH_2 at about 43 GPa.[32] However, the obtained phase transition sequences of NbH_2 were not in agreement with each other. In recent experiments, the tantalum dihydride phase was synthesized at about 5 GPa. Despite large amounts of experimental research on TaH_2 [36, 37, 38, 39], there are few theoretical studies on the high-pressure phase transition of TaH_2 and its mechanical properties, chemical bonding nature, dynamical properties, and superconductivity under high pressures. Therefore, this stimulates us to explore of high-pressure structures of MH_2 ($M = Nb, Ta$) and completely understand the structural characters, mechanical properties, electronic properties, and superconductivity of both dihydrides.

In this paper, we examine in detail the crystal structures of MH_2 ($M = Nb, Ta$) within the pressure range of 0–300 GPa by employing an ab initio evolutionary algorithm in combination with first-principles calculations. Interestingly, our calculated results show that NbH_2 and TaH_2 adopt the $Fm\bar{3}m$ and $P6_3mc$ structure, respectively, at low pressures. However, at high pressures, NbH_2 and TaH_2 possess the same $Pnma$ phases. Band structures and density of states indicate that these structures are

metallic, while the estimated T_c are 0.945–1.836 K for $Fm\bar{3}m$ - NbH_2 at 1 atm, 0.775–1.528 K for $P6_3mc$ - TaH_2 at 1 atm, 4.485–6.795 K for $Pnma$ - NbH_2 at 100 GPa, and 3.586–5.542 K for $Pnma$ - TaH_2 at 100 GPa, respectively. In addition, the analyses of the Poisson's ratio, electron localization function (ELF), and Bader charge show that these phases are ionic crystals with the charges transferring from the metal atom to H. Furthermore, the calculation results of pressure-temperature phase diagram of MH_2 ($M = Nb, Ta$) based on the quasi-harmonic approximation method indicate that high temperature and low pressure are more favorable to synthesize high pressure phase of MH_2 ($M = Nb, Ta$). Our present research attempts to better understand the behavior and properties of MH_2 ($M = Nb, Ta$) under pressure and temperature, and promote further experimental and theoretical research on transition metal hydrides.

2. Computational methods

We use the evolutionary algorithm USPEX code (Universal Structure Predictor: Evolutionary Xtallograph) to predict crystal structure, so as to extensively explore stable low-energy structures under high pressure with a different number of formula units (f.u.) at zero temperature.[40, 41, 42] A similar method has been successfully applied to discover transition metal dichalcogenides under high pressure with a similar composition to MH_2 ($M = Nb, Ta$) and provides good guidance for the synthesis of experiments.[43, 44] Here, we have predicted the crystal structure of MH_2 ($M = Nb, Ta$) at 1 atm, 50, 100, 150, 200, 250, and 300 GPa, in which the unit cell is as high as 8 formula units. The 50 structures of the first generation are randomly generated by the evolutionary algorithm, 60% of the structures of each subsequent generation come from the parent generation, and the new structures of each subsequent generation are generated by mutation operator inheritance (60%), substitution (10%) and lattice mutation (30%). The energy calculations, electronic structure calculations, and elastic properties introduced in this paper are carried out in density functional theory within the Perdew–Burke–Ernzerhof (PBE) parameterization of the generalized gradient approximation (GGA) as implemented in the Vienna ab initio simulation software package (VASP).[45, 46] The Projector–Augmented Wave (PAW) potentials with 13 valence electrons ($4s^2 4p^6 5s^1 4d^4$) for Nb, 11 valence electrons ($5p^6 6s^2 5d^3$) for Ta, and 1 valence electron ($1s^1$) for H were applied with a plane wave basis set up to cutoff energy of 600 eV and the k-point grid with 0.2 \AA^{-1} spacing was used to sample the Brillouin zone to ensure that all enthalpy calculations are well converged to less than 1 meV/atom.[47, 48] We use Bader charge analysis[49] and electronic localization function[50, 51] to describe electronic properties. In order to determine the dynamic stability and thermodynamic properties of the studied structure, the phonon calculation is carried out by using the supercell method with PHONOPY

program.[52, 53] The independent single crystal elastic constants could be determined by applying a stress tensor generated by a small strain to an optimized unit cell. The bulk modulus (B), shear modulus (G), Young's modulus (E) and Poisson's ratio (ν) of the material were determined by Voigt–Reuss–Hill (VRH) approximation.[54] Electron-phonon coupling (EPC) parameter λ of NbH₂ and TaH₂ is performed using the density functional perturbation theory as implemented in the QUANTUM–ESPRESSO package.[55] The Projector–Augmented Wave (PAW) potentials were applied with a plane wave basis set up to cutoff energy of 60 Ry and charge density cutoff of 600 Ry. The q-point mesh of EPC calculations adopted $6\times6\times6$ for $Fm\bar{3}m$ -NbH₂, $2\times4\times2$ for $Pnma$ -NbH₂, $4\times4\times2$ for $P6_3mc$ -TaH₂, and $2\times4\times2$ for $Pnma$ -TaH₂, respectively.

3. Results and Discussion

3.1 Crystal structure searching and phase transition under pressure

Firstly, to extensively explore the stable MH₂ (M = Nb, Ta) under different pressures, we carry out the evolutionary structural search for MH₂ (M = Nb, Ta) using simulation sizes ranging from one to four MH₂ (M = Nb, Ta) formula units (f.u.) in the unit cell at 0 K with selected pressures of 1 atm, 50, 100, 150, 200, 250, and 300 GPa. Subsequently, the analysis of the predicted structures provides some candidate structures with space groups Pm , $C2/m$, $Pnma$, $Imma$, $P4/nmm$, $P\bar{3}m1$, $P6_3mc$, and $Fm\bar{3}m$ for NbH₂, and with space groups Pm , $Pnma$, $P6_3/mmc$, $P4/nmm$, $Fm\bar{3}m$, $P\bar{3}m1$, $P6_3mc$, and $P6_2m$ for TaH₂. The enthalpy-pressure (H–P) relations of the candidate structures relative to the cubic $Fm\bar{3}m$ under the pressure range of 0–300 GPa for NbH₂ and TaH₂ are presented in Fig. 1a and Fig. 1c. According to our simulation, NbH₂ and TaH₂ at 1 atm adopt the structures of $Fm\bar{3}m$ and $P6_3mc$, respectively, which is consistent with the experimental observations.[56, 36, 37, 38, 39] The fact that all the experimental and theoretical structures are successfully reconstructed in a specific pressure range verifies the rationality of our method. Under compression, we observed the orthorhombic $Pnma$ structure is favored over the cubic $Fm\bar{3}m$ phase above 48.8 GPa for NbH₂ and the hexagonal $P6_3mc$ phase above 90.0 GPa for TaH₂, which does not include zero point energy (ZPE). Because of the extremely light mass of hydrogen atoms, it is expected that quantum effects will play an important role, and the (ZPE) of hydrogen may be large enough to affect the structural stability of the calculated phase.[57] We will discuss the influence of zero point energy on phase stability in Section 3.5. The calculated equations of state (EOS) for ambient-pressure structures and the orthorhombic $Pnma$ structures show the volumetric changes are discontinuous at the transition point as plotted in Fig. 1b and Fig. 1d. We observed a volume collapse of 3.7% occur at 48.8 GPa for NbH₂, and 1.2% occur at 90.0 GPa for TaH₂, suggesting that the two-phase transitions are the first-order transition.

To further verify the stability of four structures in comparison with other M–H (M = Nb, Ta) compositions, the typical convex hull diagrams of the M–H system are plotted in Fig. S1 at 1atm, 100 GPa, 200 GPa, and 300 GPa. (Fig. S1 in the Supplementary Material) It is found that MH₂ (M = Nb, Ta) always lie on the convex hull curve, suggesting that they are thermodynamically stable under both high pressure and low pressure. Besides, we approach the pressure dependence of the MH₂ (M = Nb, Ta) decomposition reaction (see Fig. S2). (Fig. S2 in the Supplementary Material) Fig. S2a shows that NbH₂ cant decompose to $NbH + \frac{1}{2}H_2$ or $\frac{1}{3}Nb + \frac{2}{3}NbH_3$. For TaH₂, we consider three substantially different decomposition paths displayed in Fig. S2b: $\frac{1}{2}Ta_2H + \frac{3}{4}H_2$, $TaH + \frac{1}{2}H_2$, or $\frac{1}{3}Ta + \frac{2}{3}TaH_3$. Apparently, TaH₂ can be stabilized in the 0–300 GPa. Through the above discussion, we can conclude that MH₂ (M = Nb, Ta) are ground states at 0–300 GPa without phase separation.

3.2 Structural features

The crystal structures of the thermodynamically stable phases at the corresponding pressures are illustrated in Fig. 2 and their structural parameters, together with previous experimental data, are presented in Table 1 and Table S1. (Table S1 in the Supplementary Material) The $Fm\bar{3}m$ -NbH₂ phase at 1 atm, shown in Table 1, has lattice parameters of $a = b = c = 4.556$ Å, which is in good agreement with previous experimental results ($a = b = c = 4.53$ Å) with a lattice parameter difference of 0.57% and other theoretical results[56, 34, 35, 58]. For $Fm\bar{3}m$ -NbH₂ at atmospheric pressure, each Nb atom is surrounded by 8 H atoms to form a regular NbH₈ cube with an Nb–H separation of 1.973 Å (see Fig. 2a). For $Pnma$ phase at 100 GPa, each Nb atom is surrounded by 9 H atoms (see Fig. 2b). The Nb–H distances range from 1.785 Å to 2.063 Å, and the H–Nb–H angles range from 57° to 121°, which indicates that the NbH₉ arrangement in $Pnma$ phase is a highly distorted tetrakaidecahedron. Obviously, with the increase of pressure, the Nb–H environment in NbH₂ changes from regular NbH₈ cube to highly distorted NbH₉ tetrakaidecahedron.

For the $P6_3mc$ -TaH₂ at ambient pressure, the lattice parameter ($a = b = 3.231$ Å, $c = 5.162$ Å) is in excellent agreement with the previous results ($a = b = 3.222$ Å, $c = 5.153$ Å) calculated by Zhuang *et al.*[59] and experimental data ($a = b = 3.223$ Å, $c = 5.143$ Å),[39] with a lattice constant deviation of 0.4%. The third–order Birch–Murnaghan equation of state (EOS[60]) is used to determine the bulk modulus B_0 , its pressure derivative B_0' and the unit cell volume V_0 at ambient conditions of $P6_3mc$ -TaH₂ (see Table 1).

By fitting for $P6_3mc$ -TaH₂, the following parameters are obtained: $B_0 = 180$ GPa, $B_0' = 4.08$, and $V_0 = 23.34$ Å³. These values are in agreement with previous Energy-dispersive x-ray diffraction studies ($B_0 = 210(20)$ GPa, $B_0' = 4$, and $V_0 = 23.14$ Å³[39]). As displayed in Fig. 2c, each Ta atom is surrounded by one H atom at a separa-

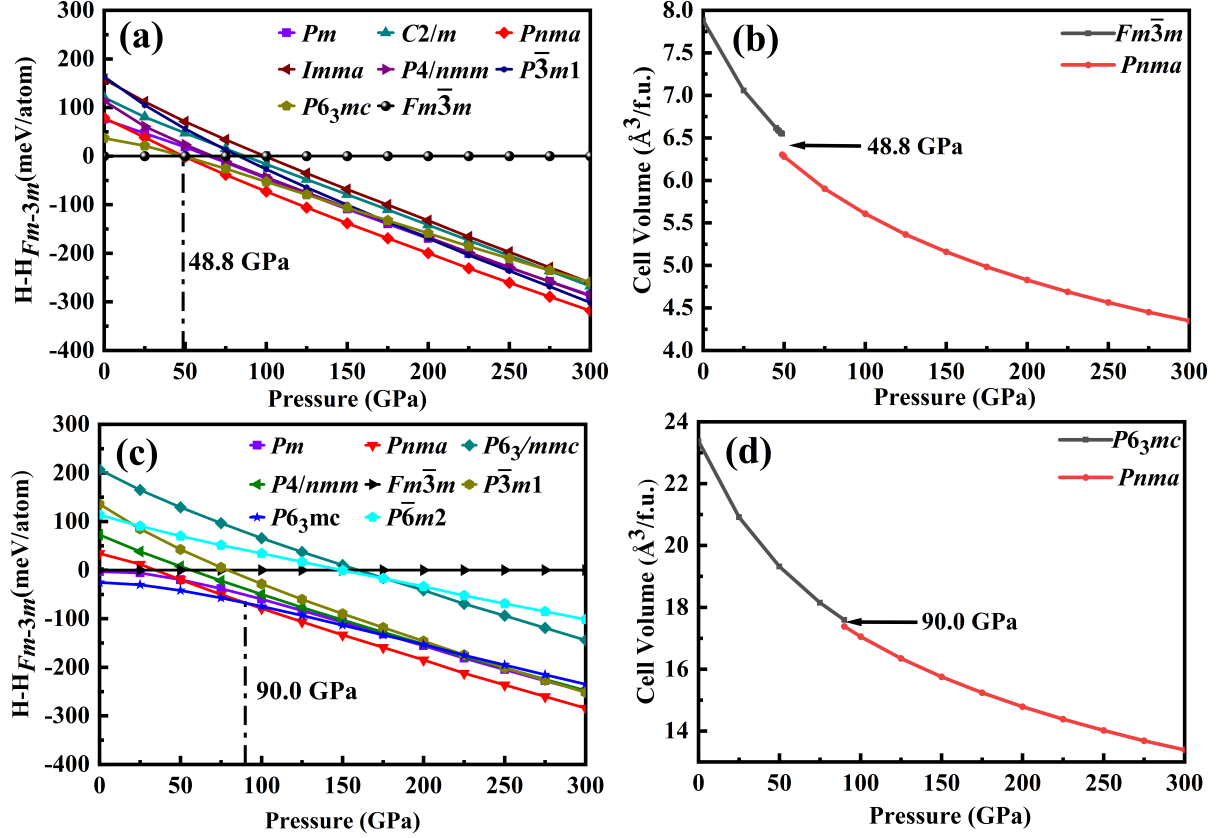


Figure 1: (a) Enthalpy-pressure relation concerning the $Fm\bar{3}m$ phase and (b) volume-pressure relations for NbH_2 . (c) Enthalpy-pressure relation concerning the $Fm\bar{3}m$ phase and (d) volume-pressure relations for TaH_2 .

Table 1: Compound MH_2 ($M = Nb, Ta$) unit cell lattice parameters, volume, bulk modulus B_0 , and its pressure derivative B'_0 at selected pressure.

	Space group	Pressure	Refs	a (Å)	b (Å)	c (Å)	V (Å ³)	B_0 (GPa)	B'_0
NbH_2	$Fm\bar{3}m$	1 atm	This work	4.556				178	3.92
			Experiment[56]	4.530					
			Calculation[32]	4.558					
			Calculation[58]	4.577					
NbH_2	$Pnma$	100 (GPa)	This work	4.682	2.838	5.067			
			Calculation[34]	4.704	2.860	5.085			
			Calculation[58]	4.696	2.862	5.092			
TaH_2	$P6_3mc$	1 atm	This work	3.231	3.231	5.162	23.34	180	4.08
			Calculation[59]	3.222	3.222	5.153			
			Experiment[39]	3.223	3.223	5.143	23.14	210(20)	4
TaH_2	$Pnma$	100 (GPa)	This work	4.709	2.842	5.095	17.04		

tion of 1.889 Å, three H atoms at a separation of 1.921 Å, and a further three H atoms at a separation of 1.990 Å. In addition, the H–Ta–H angles vary from 68° to 115°. Therefore, the Ta environment in the $P6_3mc$ configuration can be described as distorted TaH_7 decahedrons. In the $Pnma$ phase at 100 GPa (see Fig. 2d), the Ta–H distances range from 1.787 to 2.06 Å and the H–Ta–H angles vary from 58° to 164°. These results describe that the Ta environment in the $Pnma$ phase is strongly distorted TaH_9 tetrakaidcahedron. In short, the structural features of $P6_3mc$ and $Pnma$ TaH_2 can be summarized as slightly distorted TaH_7 decahedrons and strongly distorted TaH_9 tetrakaidcahedron, respectively.

3.3 Mechanical stability, mechanical properties and electronic properties

To inspect the mechanical stabilities of MH_2 ($M = Nb, Ta$) structures, we calculated the elastic constants of MH_2 ($M = Nb, Ta$) at different pressures by using the strain–stress method, as summarized in Table 2. As given in Table 2, four phases satisfy their respectively mechanical stability standards, which states that four structures are mechanically stable. Besides, Fig. S3 shows that the $Pnma$ - NbH_2 and $Pnma$ - TaH_2 are dynamically stable at 1 atm, which means that the high-pressure phases $Pnma$ - NbH_2 and $Pnma$ - TaH_2 can be quenched to normal pressure. (Fig. S3 in the Supplementary Material) At

Table 2: The calculated elastic constants C_{ij} (GPa), bulk modulus B (GPa), shear modulus G (GPa), Young's modulus E (GPa), B/G , Poisson's ratio ν , and hardness H_v (GPa) for NbH₂ and TaH₂ at the selected pressures.

	Phase	C_{11}	C_{22}	C_{33}	C_{44}	C_{55}	C_{66}	C_{12}	C_{13}	C_{23}	B	G	E	B/G	ν	H_v
NbH ₂	$Fm\bar{3}m$ @1 atm	273			84			133			180	78	204	2.31	0.31	6.6
	$Pnma$ @1 atm	273	242	248	77	68	81	102	89	121	154	75	193	2.07	0.29	7.6
TaH ₂	$P6_3mc$ @1 atm	312		313	78		73	166	95		183	83	216	2.20	0.30	7.5
	$Pnma$ @1 atm	288	284	263	74	70	85	140	105	122	174	77	200	2.27	0.31	6.6
MgH ₂ [61]	$P4_2/mnm$ @1 atm	74.4		136.0	37.6		53.0	38.8	31.4		54.2	37.8	92.1			
TiH ₂ [62]	$Pnma$ @1 atm	262.6	273.3	248.0	45.1	83.7	13.4	55.8	104.8	75.6	139.5	51.5	51.5	2.71		

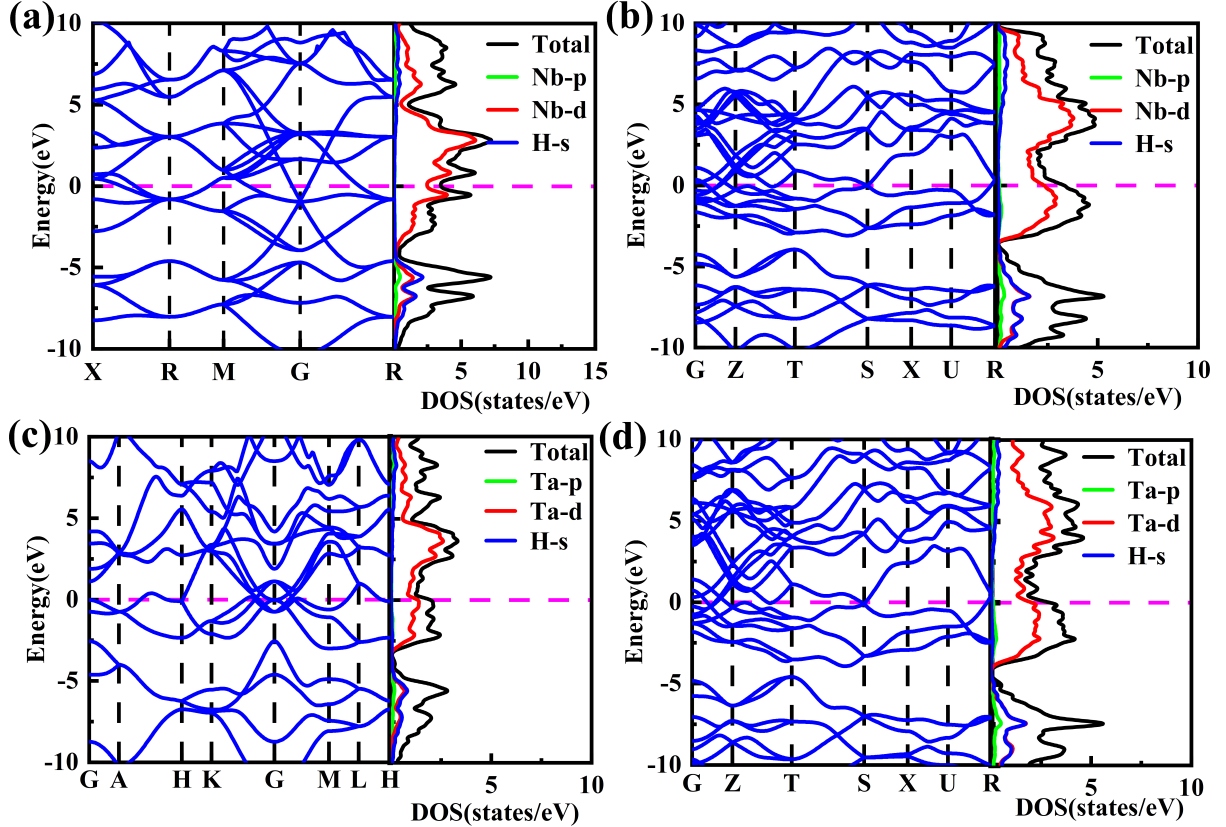


Figure 3: The electronic band structure and densities of states (DOS) of (a) $Fm\bar{3}m$ -NbH₂ at 1 atm, (b) $Pnma$ -NbH₂ at 100 GPa, (c) $P6_3mc$ -TaH₂ at 1 atm, and (d) $Pnma$ -TaH₂ at 100 GPa.

the same time, the bulk modulus (B) and shear modulus (G), B/G , Young's modulus (E), and Poisson's ratio (ν) can be derived from the calculated elastic constants on the basis of the Voigt–Reuss–Hill method. Firstly, the bulk modulus B of $Fm\bar{3}m$ -NbH₂ and $P6_3mc$ -TaH₂ is consistent with the zero-pressure bulk modulus B_0 fitted by EOS (see Table 1), which underlines the accuracies of our calculations. The calculated bulk modulus (B), shear modulus (G), and Young's modulus (E) of MH₂ at 1 atm are all larger than those of MgH₂ [61] and $Pnma$ -TiH₂ [62] hydrogen storage materials, implying that these MH₂ dihydrides present good mechanical properties. As we all know, the ductility or brittleness of materials can be estimated by the value of B/G with 1.75 as the critical value. Our results show that the calculated identical ratio values of B/G for $Fm\bar{3}m$ -NbH₂, $Pnma$ -NbH₂, $P6_3mc$ -TaH₂,

and $Pnma$ -TaH₂, are 2.31, 2.07, 2.20, and 2.27, respectively, indicating their toughness behavior. Poisson's ratio is an important parameter to describe the type of bonding in a material.[64] The threshold value of Poisson's ratio ν for covalent, and ionic materials is 0.25: large ν values (> 0.25) correspond to ionic or metallic materials, while smaller ν values (< 0.25) correspond to covalent materials. The Poisson's ratios of $Fm\bar{3}m$ -NbH₂, $Pnma$ -NbH₂, $P6_3mc$ -TaH₂, and $Pnma$ -TaH₂, are all larger than 0.25, suggesting that they can be classified into ionic materials and the ionic bond component is dominant. Vickers hardness was estimated according to the empirical model proposed by Chen *et al.*[65] This model is applied as follows: $H_v = 2(K^2G)^{0.585} - 3$, where $K = G/B$. The estimated hardness values are 6.6 GPa for $Fm\bar{3}m$ -NbH₂, 7.6 GPa for $Pnma$ -NbH₂, 7.5 GPa for $P6_3mc$ -TaH₂, and 6.6

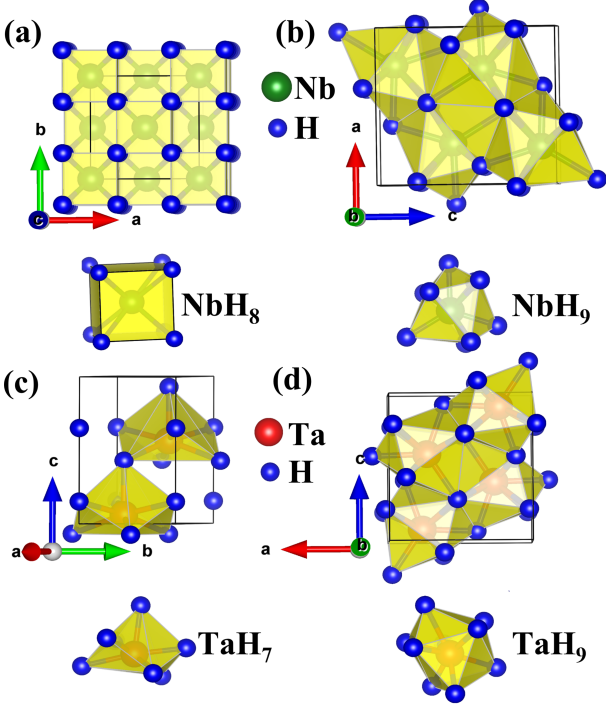


Figure 2: Crystal Structures of MH_2 ($M = Nb, Ta$). The selected stable phases for MH_2 ($M = Nb, Ta$). Green atoms depict Nb and red atoms depict Ta, while blue atoms present H, (a) $Fm\bar{3}m$ NbH_2 at 1 atm, (b) $Pnma$ NbH_2 at 100 GPa, (c) $P6_3mc$ TaH_2 at 1 atm, and (d) $Pnma$ TaH_2 at 100 GPa.

GPa for $Pnma$ - TaH_2 at 1 atm, which are lower than that of Pd_2Mo_3N with the strong three-dimensional covalent network (17.1 GPa [66]). Due to strong ionic bonds, the hardness values of all MH_2 ($M = Nb, Ta$) phases are lower than 10 GPa.

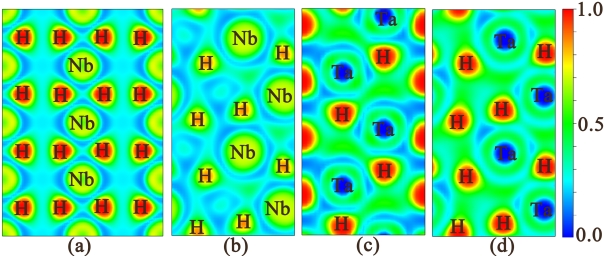


Figure 4: Electron localization function (ELF) of for stable MH_2 ($M = Nb, Ta$) phases: (a) (-110) plane for the $Fm\bar{3}m$ - NbH_2 phase at 1 atm, (b) (010) plane for the $Pnma$ - NbH_2 phase at 100 GPa, (c) (110) plane for the $P6_3mc$ - TaH_2 phase at 1 atm, and (d) (010) plane for the $Pnma$ - TaH_2 phase at 100 GPa.

To further gain insight into the electronic properties of four stable MH_2 ($M = Nb, Ta$) compounds, we calculated the electronic band structures and densities of states (DOS), as displayed in Fig. 3. We can see that they all exhibit metallic characteristics, confirmed by the overlap between the conduction bands and the valence bands, and the finite electronic DOS at the Fermi level (E_f). The metallic behavior of these phases indicates that these ma-

Table 3: Calculated Bader charges for NbH_2 and TaH_2 at the selected pressures. δ represents the amount of charge transferred from metal atom to H atom.

Phase	Space group	Pressure	Atom	Charge value (e)	δ (e)
NbH_2	$Fm\bar{3}m$	1 atm	Nb	11.70	1.30
			H	1.65	-0.65
	$Pnma$	100 (GPa)	Nb	11.98	1.02
			H	1.51	-0.51
TaH_2	$P6_3mc$	1 atm	Ta	9.82	1.18
			H	1.59	-0.59
	$Pnma$	100 (GPa)	Ta	9.96	1.04
			H	1.52	-0.52

terials may be magnetic. We have carried out calculations taking into account the spin polarization. Results suggest that MH_2 ($M = Nb, Ta$) are all nonmagnetic because the magnetic moment of each metal atom is zero. For these phases, it is found that there is a deep valley below the Fermi level and the localized hybridization between $M-d$ and $H-s$ is observed in the energy region below the pseudogap, while the contributions of $M-d$ ($M = Nb, Ta$) states mainly dominate in this energy range above pseudogap, so the metallic properties are mainly due to partially filled $Nb-4d$ or $Ta-5d$ shell. Note that the contribution from $H-s$ states at the Fermi level is almost zero, which is of great significance to superconductivity according to previous studies.

To clarify the bonding characteristics for these phases MH_2 ($M = Nb, Ta$), we calculated the electronic localization function (ELF), as depicted in Fig. 4. It is worthy pointing out that these four crystals display a common feature of the ELF that there is no electron localization toward the neighboring $M-H$ ($M = Nb, Ta$) and $H-H$ connections, thus suggesting that no covalent interaction exists for neighboring $M-H$ ($M = Nb, Ta$) and $H-H$. Moreover, the ELF values between M ($M = Nb, Ta$) and the nearest H atom in four crystals are all smaller than 0.5, implying that ionic bonds are present between M ($M = Nb, Ta$) and H atoms. This conclusion also demonstrates the validity of the analyses of Poisson's ratio.

In addition, in order to evaluate the strength of ionic bonds, we explicitly calculated the actual charge transfer between M ($M = Nb, Ta$) and H atoms, which is summarized in Table 3. Each H atom respectively gains approximately 0.65 e, 0.51 e, 0.59 e, and 0.52 e for $Fm\bar{3}m$ - NbH_2 , $Pnma$ - NbH_2 , $P6_3mc$ - TaH_2 , and $Pnma$ - TaH_2 , while the M ($M = Nb, Ta$) atoms lose approximately 1.30 e, 1.02 e, 1.18 e, and 1.04 e. Therefore, there is a large amount of charge transfer from M ($M = Nb, Ta$) to the H atoms, demonstrating the ionic character of the $M-H$ bonding in MH_2 ($M = Nb, Ta$) crystals. Such ionic bonding properties are similar in RhH_2 , [14] ThH_2 , [67] TcH_2 , [68] TiH_2 , [69] HfH_2 , [20] and VH_2 , [70, 71] but differ from many hydrogen-rich polycrystalline forms (i.e. SiH_4 , [72] SnH_4 , [73] MgH_{12} , [74] MgH_{16} , AsH_8 , [75] RuH_6 , [76] and MoH_{11} [77]) where H atoms are bonded to the nearest H atoms to form H_2 or H_3 units and/or they are covalently bonded to X ($X = Si, Sn$) to

form X–H bonds. Combination analysis of ELF and Bader charges reveals that MH_2 ($M = Nb, Ta$) forms an ionic bond between M ($M = Nb, Ta$) and H, and MH_2 ($M = Nb, Ta$) belongs to ionic crystal with the charge transfers from M atom to H atom, which is consistent with Poisson’s ratio analysis mentioned above.

3.4 Electron-phonon coupling

For exploring the superconductivity, we calculate the logarithmic average phonon frequency ω_{log} , the electronic DOS at the Fermi level $N(E_f)$, and the EPC parameter λ as shown in Table 4. It is found that for materials with $\lambda < 1.5$, it is more accurate to estimate the superconducting temperature of the obtained structure by using the modified Allen-Dynes McMillan equation[78] $T_c = \frac{\omega_{log}}{1.2} \exp \left[\frac{1.04(1+\lambda)}{\lambda - \mu(1+0.62\lambda)} \right]$. The estimated T_c of NbH_2 and TaH_2 with a typical choice of Coulomb pseudopotential $\mu^* = 0.1-0.13$ is presented in Table 4, which shows that $Pnma-NbH_2$ has the highest T_c , and can reach 6.9 K at 50 GPa, higher than the maximal 4 K predicted for $Pnma-VH_2$ [32] at 60 GPa. The estimated T_c of $P6_3mc-TaH_2$ is 0.775–1.528 K at 1 atm, which is consistent with the experimental measurement of no superconducting transition in the temperature range of 4.4–300 K for TaH_2 . [37] In addition, the calculated T_c of the $Pnma-TaH_2$ are 3.586–5.542 K at 100 GPa, which is smaller than that of the $Pnma-NbH_2$ at 100 GPa. The main reason is that the electron DOS of $Pnma-TaH_2$ at Fermi level $N(E_f)$ is much smaller than that of $Pnma-NbH_2$.

According to Figure 5, we computed phonon dispersions, phonon density of states (PHDOS), Eliashberg spectral function ($\alpha^2F(\omega)/\omega$), and EPC integrated ($\lambda(\omega)$) for the $Fm\bar{3}m-NbH_2$ and $P6_3mc-TaH_2$ at 1 atm, and the $Pnma-NbH_2$ and $Pnma-TaH_2$ at 100 GPa. As a result, we found that all structure is dynamically stable because it exhibits the absence of any imaginary Frequencies.[79] A clear gap between acoustic and optical phonon modes is observed in the theoretical phonon density of states (Fig. 5), which is due to the huge difference in mass between M ($M = Nb, Ta$) atom and H atom, thus dividing the phonon density of states into low-frequency vibrations of M ($M = Nb, Ta$) atom and high-frequency vibrations of H atom. Note that the low-frequency vibrational modes below 10 THz come from M atoms, accounting for 90.8%, 85.5%, 84.5%, and 78% of the total λ , respectively, while the high-frequency vibrational modes above 10 THz come from H atoms, accounting for 9.2%, 14.5%, 15.5%, and 22% of the total λ , respectively. We therefore conclude that the coupling between electron and phonon vibration of M ($M = Nb, Ta$) is the reason why MH_2 ($M = Nb, Ta$) shows superconductivity, which is consistent with the dominant DOS of $M-d$ ($M = Nb, Ta$) shell at Fermi energy. For MH_2 ($M = Nb, Ta$), contrary to the case of superconducting H_3S [84, 85], YH_3 [86], and PdH [87], the electron-optical phonon contribution and consequently to T_c is small, due essentially to the low value of the DOS of H- s states at the Fermi energy, which leads to the low- T_c

features of all MH_2 ($M = Nb, Ta$) phases.

3.5 Pressure-temperature phase diagram

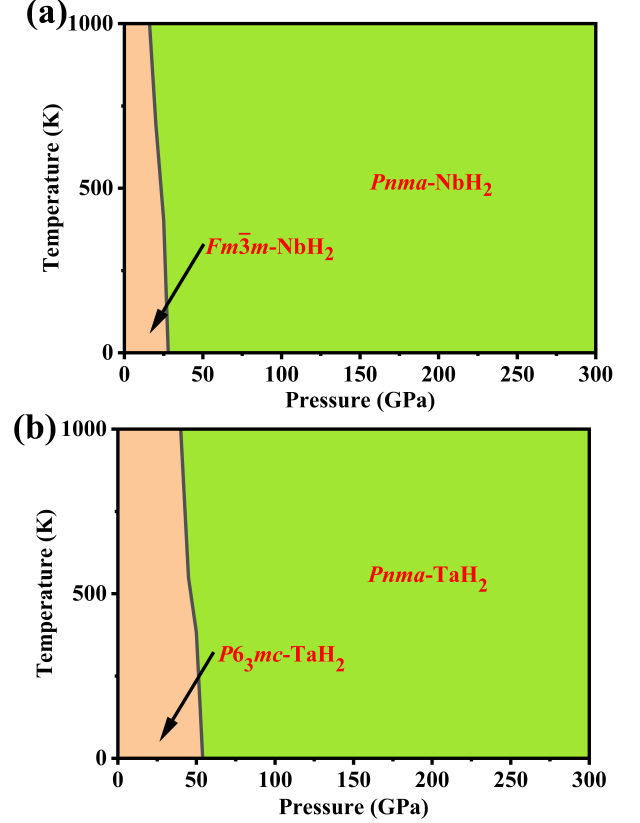


Figure 6: Calculated temperature-pressure phase diagram of (a) NbH_2 and (b) TaH_2 based on the the quasi-harmonic approximation.

As discussed earlier, we established a phase transition sequence of MH_2 ($M = Nb, Ta$) under pressure at 0 K. High pressure and high-temperature technology are very important for the synthesis of new materials. Here, the main function of pressure and temperature is to change the free energy diagram of materials or the reaction barrier between materials, so as to promote phase transition or chemical reaction, which leads to the formation and synthesis of the target phase, which can be stored in environmental conditions. To further discover the high-pressure synthesis conditions and the stable pressure-temperature region of each phase, the phase diagram of MH_2 ($M = Nb, Ta$) was constructed by using the quasi-harmonic approximation (QHA) method.[53] At a given pressure and temperature, the Helmholtz free energy is expressed as:

$$F(V, T) = E(V) + F_{vib}(V, T) + F_{el} \quad (1)$$

Where $E(V)$ is the cold static lattice energy with atoms being clamped at their equilibrium positions, $F_{vib}(V, T)$ is the nonequilibrium vibrational Helmholtz free energy of phonons, and F_{el} is the electronic thermal excitation free energy. Of course, considering that the contribution of thermoelectrons (F_{el}) to free energy is negligible at relatively low temperatures [88, 89, 90], the $F(V, T)$ we obtain

Table 4: The calculated logarithmic average phonon frequency ω_{\log} , the electronic density of states at the Fermi level $N(E_f)$ (states/spin/Ry/Unit cell), electron-phonon coupling parameters λ , and superconducting critical temperatures T_c of $Fm\bar{3}m$ -NbH₂, $Pnma$ -NbH₂, $P6_3mc$ -TaH₂, and $Pnma$ -TaH₂ at different pressures.

Phase	Structure	Pressure	ω_{\log}	$N(E_f)$	λ	$T_c(K)\mu^* = 0.1$	$T_c(K)\mu^* = 0.13$
NbH ₂	$Fm\bar{3}m$	1atm	262.565	7.208	0.441	1.836	0.945
	$Pnma$	50 (GPa)	376.899	26.477	0.560	6.903	4.668
		100 (GPa)	394.013	20.208	0.550	6.795	4.485
		300 (GPa)	547.141	16.527	0.554	9.694	6.439
TaH ₂	$P6_3mc$	1atm	229.106	10.402	0.436	1.528	0.775
		50 (GPa)	297.577	7.146	0.325	0.299	0.071
	$Pnma$	100 (GPa)	348.496	16.927	0.537	5.542	3.586
		300 (GPa)	371.099	14.736	0.532	5.719	3.672

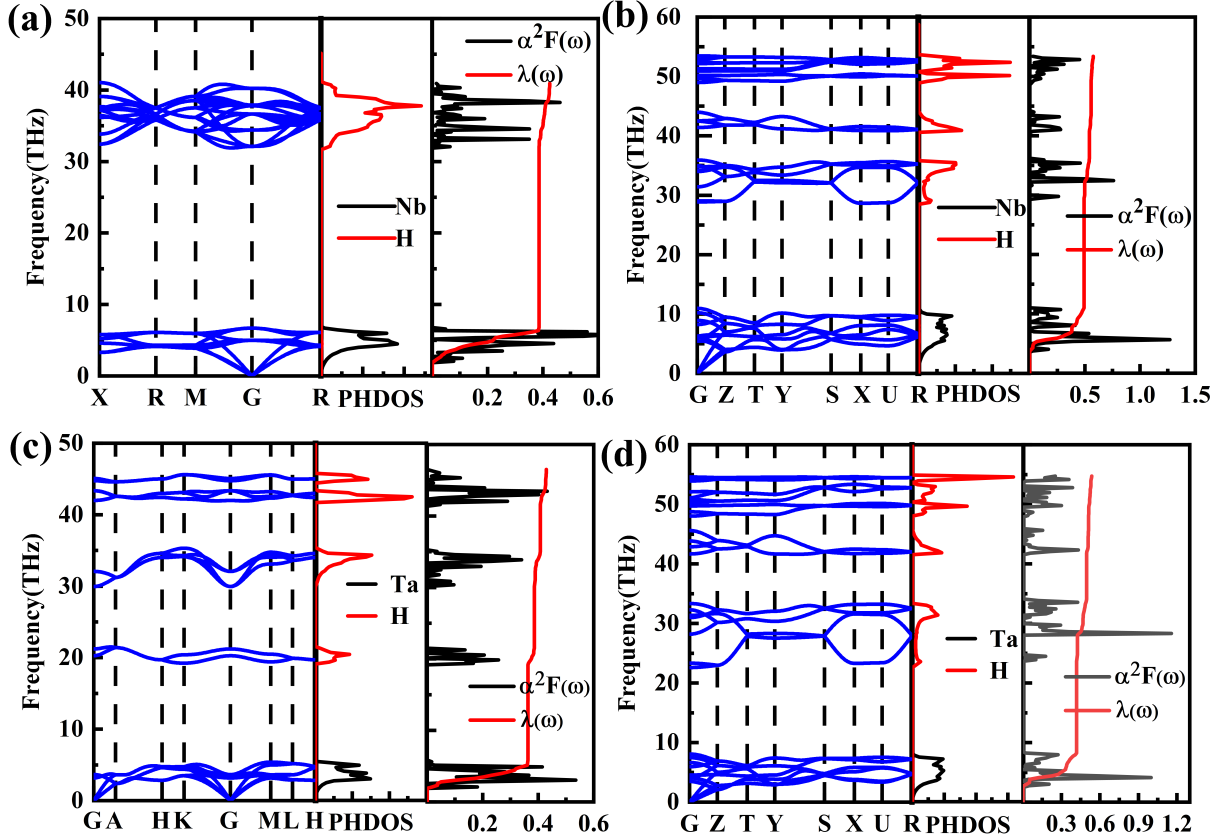


Figure 5: Phonon dispersion relations, projected phonon densities of states (PHDOS), and Eliashberg spectral function for (a) $Fm\bar{3}m$ NbH₂ at 1atm, (b) $Pnma$ NbH₂ at 100 GPa, (c) $P6_3mc$ TaH₂ at 1 atm, and (d) $Pnma$ TaH₂ at 100 GPa.

does not include the contribution of electrons. $F_{\text{vib}}(V, T)_{436}$ can be obtained from

$$F_{\text{vib}}(V, T) = \int_0^\infty \left[\frac{\hbar\omega}{2} + \kappa_B T \ln \left(1 - e^{-\hbar\omega/\kappa_B T} \right) \right] g(\omega, V) d\omega \quad (2)$$

Where κ_B is Boltzmann's constant and $g(\omega, V)$ is the phonon density of state and depends on the crystal geometry. Then, the Gibbs free energy is given by

$$G_{\text{gibbs}} = F(V, T) - V \left(\frac{\partial F}{\partial V} \right)_T \quad (3)$$

Therefore, based on the calculated Gibbs free energies of these phases at different temperatures and pressures, we

obtain a pressure-temperature phase diagram (Fig. 6), which can determine the possible existence region of MH₂ (M = Nb, Ta) phases. According to Fig. 6, by comparing the transition pressures with and without the influence of temperature, we find that the transition pressure of the transition pressure of NbH₂ from $Fm\bar{3}m$ phase to $Pnma$ phase at 0 K is 27.9 GPa, while TaH₂ from $P6_3mc$ phase to $Pnma$ phase at 0 K is 54.0 GPa. Therefore, ZPE does not change the phase transition series, but only reduces the phase transition pressure, especially for high-pressure transition, which is also observed in other hydrides, such as MgH₆, [91] AcH₂, [92] and PtH [93]. It is obvious that the transition pressures of $Fm\bar{3}m$ -NbH₂ \rightarrow $Pnma$ -NbH₂ and $P6_3mc$ -

$\text{TaH}_2 \rightarrow \text{Pnma}$ - TaH_2 decrease obviously with the increase of temperature, which originates mainly from the contributions of the thermal vibration at the atomic position to the high-pressure structures more significantly than the low-pressure structures, thus significantly expanding their high-pressure structural stability fields.

4. Conclusion

In a word, we have extensively investigated the systematic structure evolution of MH_2 ($\text{M} = \text{Nb}, \text{Ta}$) compounds in the pressure range of 0 to 300 GPa by ab initio evolutionary simulation. Based on the structural prediction, the phase transition sequence of NbH_2 is $\text{Fm}\bar{3}m \rightarrow \text{Pnma}$, while the TaH_2 is $\text{P6}_3\text{mc} \rightarrow \text{Pnma}$ at 90.0 GPa, respectively. The calculations of elastic constants and phonon dispersions confirmed that these phases are stable. The analyses of DOS, Poisson's ratio, ELF, and Bader charge indicate that four MH_2 ($\text{M} = \text{Nb}, \text{Ta}$) phases are metallic and an ionic crystal with large amounts of charge transferring from M ($\text{M} = \text{Nb}, \text{Ta}$) atom to H . The estimated superconducting transition temperature T_c values of Pnma - NbH_2 are 6.903 K at 50 GPa. In addition, it is found that the high-pressure phase transition of MH_2 ($\text{M} = \text{Nb}, \text{Ta}$) is more favorable upon heating, and this originates mainly from the contributions of the thermal vibration at the atomic position. The current research will stimulate further high-temperature and high-pressure experiments to synthesize these transition metal dihydrides and make structural, mechanical, and superconducting measurements.

Conflicts of interest

Authors declare no conflicts to interest.

Acknowledgements

This work was supported by the National Natural Science Foundation of China (No. 11804031, 11904297 and 11747139), the Scientific Research Project of Education Department of Hubei Province (No. Q20191301) and Talent and High Level Thesis Development Fund of Department of Physics and Optoelectronic Engineering of Yangtze University (C. Z. Z.).

References

- [1] Troyan, I.A., Semenok, D.V., Kvashnin, A.G., Sadakov, A.V., Sobolevskiy, O.A., Pudalov, V.M., Ivanova, A.G., Prakapenka, V.B., Eran Greenberg, A.G.G., Lyubutin, I.S., Struzhkin, V.V., Bergara, A., Errea, I., Bianco, R., Calandra, M., Mauri, F., Monacelli, L., Akashi, R., Oganov, A.R., 2021. Anomalous high-temperature superconductivity in YH_6 . *Adv. Mater.* 33, 2006832.
- [2] Kong, P.P., Minkov, V.S., Kuzovnikov, M.A., Drozdov, A.P., Besedin, S.P., Mozaffari, S., Balicas, L., Balakirev, F.F., Prakapenka, V.B., Chariton, S., Knyazev, D.A., Greenberg, E., Eremets, M.I., 2021. Superconductivity up to 243 K in the yttrium-hydrogen system under high pressure. *Nat. Commun.* 12, 1–9.
- [3] Snider, E., Dasenbrock-Gammon, N., McBride, R., Wang, X.Y., Meyers, N., Lawler, K.V., Zurek, E., Salamat, A., Dias, R.P., 2021. Synthesis of yttrium superhydride superconductor with a transition temperature up to 262 K by catalytic hydrogenation at high pressures. *Phys. Rev. Lett.* 126, 117003.
- [4] Salke, N.P., Esfahani, M.M.D., Zhang, Y.J., Kruglov, I.A., Zhou, J.S., Wang, Y.G., Eran Greenberg, V.B.P., Liu, J., Oganov, A.R., Lin, J.F., 2019. Synthesis of clathrate cerium superhydride CeH_9 at 80–100 GPa with atomic hydrogen sublattice. *Nat. Commun.* 10, 1–10.
- [5] Li, X., Huang, X.L., Duan, D.F., Pickard, C.J., Zhou, D., Xie, H., Zhuang, Q., Huang, Y.P., Zhou, Q., Liu, B.B., Cui, T., 2019. Polyhydride CeH_9 with an atomic-like hydrogen clathrate structure. *Nat. Commun.* 10, 1–7.
- [6] Chen, W.H., Semenok, D.V., Huang, X.L., Shu, H., Li, X., Duan, D.F., Cui, T., Oganov, A.R., 2021. High-temperature superconducting phases in cerium superhydride with a T_c up to 115 K below a pressure of 1 megabar. *Phys. Rev. Lett.* 127, 117001.
- [7] Semenok, D.V., Kvashnin, A.G., Ivanova, A.G., Svitlyk, V., Fominski, V.Y., Sadakov, A.V., Sobolevskiy, O.A., Pudalov, V.M., Troyan, I.A., Oganov, A.R., 2020. Superconductivity at 161 K in thorium hydride ThH_{10} : Synthesis and properties. *Mater. Today* 33, 36–44.
- [8] Drozdov, A.P., Kong, P.P., Minkov, V.S., Besedin, S.P., Kuzovnikov, M.A., Mozaffari, S., Balicas, L., Balakirev, F.F., Graf, D.E., Prakapenka, V.B., Greenberg, E., Knyazev, D.A., Tkacz, M., Eremets, M.I., 2019. Superconductivity at 250 K in lanthanum hydride under high pressures. *Nature* 569, 528–531.
- [9] Hong, F., Shan, P.F., Yang, L.X., Yue, B.B., Yang, P.T., Liu, Z.Y., Sun, J.P., Dai, J.H., Yu, H., Yin, Y.Y., Yu, X.H., Cheng, J.G., Zhao, Z.X., 2021. Superconductivity at 70 K in tin hydride SnH_x under high pressure. *arXiv preprint arXiv:2101.02846*.
- [10] Talantsev, E.F., 2021. Comparison of highly-compressed $\text{C2}/m$ - SnH_{12} superhydride with conventional superconductors. *J. Phys. Condens. Matter* 33, 285601.
- [11] Kruglov, I.A., Kvashnin, A.G., Goncharov, A.F., Oganov, A. R., Lobanov, S.S., Holtgrewe, N., Jiang, S., Prakapenka, V.B., Greenberg, E., Yanilkin, A.V., 2018. Uranium polyhydrides at moderate pressures: Prediction, synthesis, and expected superconductivity. *Sci. Adv.* 4, eaat9776.
- [12] Ma, L., Wang, K., Xie, Y., Yang, X., Wang, Y.Y., Zhou, M., Liu, H.Y., Yu, X.H., Zhao, Y.S., Wang, H.B., Liu, G.T., Ma, Y.M., 2022. High-temperature superconducting phase in clathrate calcium hydride CaH_6 up to 215 K at a pressure of 172 GPa. *Phys. Rev. Lett.* 128, 167001.
- [13] Li, Z.W., He, X., Zhang, C.L., Wang, X.C., Zhang, S.J., Jia, Y.T., Feng, S.M., Lu, K., Zhao, J.F., Zhang, J., Min, B.S., Long, Y.W., Yu, R.C., Wang, L.H., Ye, M.Y., Zhang, Z.S., Prakapenka, V., Chariton, S., Ginsberg, P.A., Bass, J., Yuan, S.H., Liu, H.Z., Jin, C.Q., 2022. Superconductivity above 200 K discovered in superhydrides of calcium. *Nat. Commun.* 13, 1–5.
- [14] Shao, Z.J., Duan, D.F., Wang, L.Y., Song, H., Yu, H.Y., Yao, Y.S., Cui, T., 2021. First-principles investigation of rhodium hydrides under high pressure. *Phys. Rev. B* 104, 054110.
- [15] Miao, M.S., Sun, Y.H., Zurek, E., Lin, H.Q., 2020. Chemistry under high pressure. *Nat. Rev. Chem.* 4, 508–527.
- [16] Li, B., Ding, Y., Kim, D.Y., Ahuja, R., Zou, G.T., Mao, H.K., 2011. Rhodium dihydride (RhH_2) with high volumetric hydrogen density. *Proc. Natl. Acad. Sci. U.S.A.* 108, 18618–18621.
- [17] Scheler, T., Marqués, M., Konôpková, Z., Guillaume, C.L., Howie, R.T., Gregoryanz, E., 2013. High-pressure synthesis and characterization of iridium trihydride. *Phys. Rev. Lett.* 111, 215503.
- [18] Kim, D.Y., Scheicher, R.H., Pickard, C.J., Needs, R.J., Ahuja, R., 2011. Predicted formation of superconducting platinum-hydride crystals under pressure in the presence of molecular hydrogen. *Phys. Rev. Lett.* 107, 117002.
- [19] Miwa, K., Fukumoto, A., 2002. First-principles study on 3d transition-metal dihydrides. *Phys. Rev. B* 65, 155114.
- [20] Quijano, R., de Coss, R., Singh, D.J., 2009. Electronic structure

- and energetics of the tetragonal distortion for TiH_2 , ZrH_2 , and HfH_2 : A first-principles study. *Phys. Rev. B* 80, 184103.
- [21] Kanagaprabha, S., Asvinimeenaatci, A.T., Sudhapriyanga, G., Jemmy Cinthia, A., Rajeswarapalanichamy, R., Iyakutti, K., 2013. First principles study of stability and electronic structure of TMH and TMH_2 ($\text{TM} = \text{Y}, \text{Zr}, \text{Nb}$). *Acta Phys. Pol.* 123, 126–131.
 - [22] Smithson, H., Marianetti, C.A., Morgan, D., Van der Ven, A., Predith, A., Ceder, G., 2002. First-principles study of the stability and electronic structure of metal hydrides. *Phys. Rev. B* 66, 144107.
 - [23] Purans, J., Menushenkov, A., Besedin, S., Ivanov, A., Minkov, V., Pudza, I., Kuzmin, A., Klementiev, K., Pascarelli, S., Mathon, O., Rosa, A.D., Irifune, T., Eremets, M.I., 2021. Local electronic structure rearrangements and strong anharmonicity in YH_3 under pressures up to 180 GPa. *Nat. Commun.* 12, 1–10.
 - [24] Gao, G.Y., Bergara, A., Liu, G.T., Ma, Y.M., 2013. Pressure induced phase transitions in TiH_2 . *J. Appl. Phys.* 113, 103512.
 - [25] Kalita, P.E., Sinogeikin, S.V., Lipinska-Kalita, K., Hartmann, T., Ke, X.Z., Chen, C.F., Cornelius, A., 2010. Equation of state of TiH_2 up to 90 GPa: A synchrotron x-ray diffraction study and ab initio calculations. *J. Appl. Phys.* 108, 043511.
 - [26] Huang, X.L., Duan, D.F., Li, F.F., Huang, Y.P., Wang, L., Liu, Y.X., Bao, K., Zhou, Q., Liu, B.B., Cui, T., 2014. Structural stability and compressive behavior of ZrH_2 under hydrostatic pressure and nonhydrostatic pressure. *RSC Adv.* 4, 46780–46786.
 - [27] Liu, Y.X., Huang, X.L., Duan, D.F., Tian, F.B., Liu, H.Y., Li, D., Zhao, Z.L., Sha, X.J., Yu, H.Y., Zhang, H.D., Liu, B.B., Cui, T., 2015. First-principles study on the structural and electronic properties of metallic HfH_2 under pressure. *Sci. Rep.* 5, 11381.
 - [28] Ye, X.Q., Hoffmann, R., Ashcroft, N.W., 2015. Theoretical study of phase separation of scandium hydrides under high pressure. *J. Phys. Chem. C* 119, 5614–5625.
 - [29] Wei, Y.K., Yuan, J.N., Khan, F.I., Ji, G.F., Gu, Z.W., Wei, D.Q., 2016. Pressure induced superconductivity and electronic structure properties of scandium hydrides using first principles calculations. *RSC adv.* 6, 81534–81541.
 - [30] Choi, H.J., Roundy, D., Sun, H., Cohen, Marvin L., Louie, Steven, G., 2002. The origin of the anomalous superconducting properties of MgB_2 . *Nature* 418, 758–760.
 - [31] Bohnen, K.P., Heid, R., Renker, B., 2001. Phonon dispersion and electron-phonon coupling in MgB_2 and AlB_2 . *Phys. Rev. Lett.* 86, 5771.
 - [32] Chen, C.B., Tian, F.B., Duan, D.F., Bao, K., Jin, X.L., Liu, B.B., Cui, T., 2014. Pressure induced phase transition in MH_2 ($\text{M} = \text{V}, \text{Nb}$). *J. Chem. Phys.* 140, 114703.
 - [33] Wang, W.J., Zhang, C.Z., Jin, Y.Y., Li, S., Zhang, W.B., Kong, P.L., Xie, C.W., Du, C.Z., Liu, Q., Zhang, C.H., 2020. Structural, mechanical and electronic properties and hardness of ionic vanadium dihydrides under pressure from first-principles computations. *Sci. Rep.* 10, 8868.
 - [34] Gao, G.Y., Hoffmann, R., Ashcroft, N.W., Liu, H.Y., Bergara, A., Ma, Y.M., 2013. Theoretical study of the ground-state structures and properties of niobium hydrides under pressure. *Phys. Rev. B* 88, 184104.
 - [35] Liu, G.T., Besedin, S., Irodova, A., Liu, H.Y., Gao, G.Y., Eremets, M., Wang, X., Ma, Y.M., 2017. Nb-H system at high pressures and temperatures. *Phys. Rev. B* 95, 104110.
 - [36] Saitoh, H., Takagi, S., Sato, T., Orimo, S.i., 2021. Pressure-temperature phase diagram of Ta-H system up to 9 GPa and 600 °C. *Appl. Sci.* 11, 6719.
 - [37] Kuzovnikov, M.A., Tkacz, M., Meng, H.J., Kapustin, D.I., Kulakov, V.I., 2017. High-pressure synthesis of tantalum dihydride. *Phys. Rev. B* 96, 134120.
 - [38] Ying, J.J., Li, X., Greenberg, E., Prakapenka, V.B., Liu, H.Y., Struzhkin, V.V., 2019. Synthesis and stability of tantalum hydride at high pressures. *Phys. Rev. B* 99, 224504.
 - [39] Kuzovnikov, M.A., Antonov, V.E., Ivanov, A.S., Hansen, T., Savvin, S., Kulakov, V.I., Tkacz, M., Kolesnikov, A.I., Gurev, V.M., 2020. Neutron scattering study of tantalum dihydride. *Phys. Rev. B* 102, 024113.
 - [40] Oganov, A.R., Glass, C.W., 2006. Crystal structure prediction using ab initio evolutionary techniques: principles and applications. *J. Chem. Phys.* 124, 244704.
 - [41] Oganov, A.R., Lyakhov, A.O., Valle, M., 2011. How evolutionary crystal structure prediction works—and why. *Acc. Chem. Res.* 44, 227–237.
 - [42] Lyakhov, A.O., Oganov, A.R., Stokes, H.T., Zhu, Q., 2013. New developments in evolutionary structure prediction algorithm USPEX. *Comput. Phys. Commun.* 184, 1172–1182.
 - [43] Saqib, H., Rahman, S., Zhao, Y., Cazorla, C., Errandonea, D., Susilo, R., Zhuang, Y., Huang, Y., Chen, B., Dai, N., 2021. Evolution of structural and electronic properties of TiSe_2 under high pressure. *J. Phys. Chem. Lett.* 12, 9859–9867.
 - [44] Rahman, S., Saqib, H., Liang, X., Errandonea, D., Resta, A. S., Molina-Sanchez, A., Gao, G., Wang, L., Tian, Y., Mao, H. K., 2022. Pressure-induced metallization and robust superconductivity in pristine 1T- HfSe_2 . *Mater. Today Phys.* 25, 100698.
 - [45] Kresse, G., Furthmüller, J., 1996. Efficient iterative schemes for ab initio total-energy calculations using a plane-wave basis set. *Phys. Rev. B* 54, 11169.
 - [46] Perdew, J.P., Burke, K., Ernzerhof, M., 1996. Generalized gradient approximation made simple. *Phys. Rev. Lett.* 77, 3865.
 - [47] Kresse, G., Joubert, D., 1999. From ultrasoft pseudopotentials to the projector augmented-wave method. *Phys. Rev. B* 59, 1758.
 - [48] Monkhorst, H.J., Pack, J.D., 1976. Special points for brillouin-zone integrations. *Phys. Rev. B* 13, 5188.
 - [49] Tang, W., Sanville, E., Henkelman, G., 2009. A grid-based bader analysis algorithm without lattice bias. *J. Phys. Condens. Matter* 21, 084204.
 - [50] Becke, A.D., Edgecombe, K.E., 1990. A simple measure of electron localization in atomic and molecular systems. *J. Chem. Phys.* 92, 5397–5403.
 - [51] Savin, A., Jepsen, O., Flad, J., Andersen, O.K., Preuss, H., von Schnering, H.G., 1992. Electron localization in solid-state structures of the elements: the diamond structure. *Angew. Chem. Int. Ed.* 31, 187–188.
 - [52] Togo, A., Oba, F., Tanaka, I., 2008. First-principles calculations of the ferroelastic transition between rutile-type and CaCl_2 -type SiO_2 at high pressures. *Phys. Rev. B* 78, 134106.
 - [53] Togo, A., Tanaka, I., 2015. First principles phonon calculations in materials science. *Scr. Mater.* 108, 1–5.
 - [54] Hill, R., 1952. The elastic behaviour of a crystalline aggregate. *Proc. Phys. Soc. London, Sect. A* 65, 349.
 - [55] Giannozzi, P., Baroni, S., Bonini, N., Calandra, M., Car, R., Cavazzoni, C., Ceresoli, D., Chiarotti, G.L., Cococcioni, M., Dabo, I., Dal Corso, A., de Gironcoli, S., Fabris, S., Fratesi, G., Gebauer, R., Gerstmann, U., Gougousis, C., Kokalj, A., Lazzeri, M., Martin-Samos, L., Marzari, N., Mauri, F., Mazzearello, R., Paolini, S., Pasquarello, A., Paulatto, L., Sbraccia, C., Scandolo, S., Sclauzero, G., Seitsonen, A.P., Smogunov, A., Umari, P., Wentzcovitch, R.M., 2009. QUANTUM ESPRESSO: a modular and open-source software project for quantum simulations of materials. *J. Phys. Condens. Matter* 21, 395502.
 - [56] Reilly, J.J., Wiswall, R.H., 1970. Higher hydrides of vanadium and niobium. *Inorg. Chem.* 9, 1678–1682.
 - [57] Pickard, C.J., Needs, R.J., 2007. Structure of phase III of solid hydrogen. *Nat. Phys.* 3, 473–476.
 - [58] Zhang, C.Z., Sun, G.L., Wang, J.J., Lu, C., Jin, Y.Y., Kuang, X.Y., Hermann, A., 2017. Prediction of novel high-pressure structures of magnesium niobium dihydride. *ACS Appl. Mater. Interfaces* 9, 26169–26176.
 - [59] Zhuang, Q., Jin, X.L., Cui, T., Ma, Y.B., Lv, Q.Q., Li, Y., Zhang, H.D., Meng, X., Bao, K., 2017. Pressure-stabilized superconductive ionic tantalum hydrides. *Inorg. Chem.* 56, 3901–3908.
 - [60] Birch, F., 1947. Finite elastic strain of cubic crystals. *Phys. Rev.* 71, 809.
 - [61] Jankaew, A., Ham, B., Zhang, X., Arróyave, R., 2014. Ab-initio calculations of the elastic and finite-temperature thermo-

- dynamic properties of niobium-and magnesium hydrides. *Int. J. Hydrog. Energy* 39, 15530–15539.
- [62] Pan, Y., Chen, S., 2020. Exploring the novel structure, transportable capacity and thermodynamic properties of TiH_2 hydrogen storage material. *Int. J. Energy Res.* 44, 4997–5007.
- [63] Pugh, S., 1954. Xcii. relations between the elastic moduli and the plastic properties of polycrystalline pure metals. *Philos. Mag.* 45, 823–843.
- [64] Haines, J., Leger, J., Bocquillon, G., 2001. Synthesis and design of superhard materials. *Annu. Rev. Mater. Sci.* 31, 1.
- [65] Chen, X.Q., Niu, H.Y., Li, D.Z., Li, Y.Y., 2011. Modeling hardness of polycrystalline materials and bulk metallic glasses. *Intermetallics* 19, 1275–1281.
- [66] Errandonea, D., Ferrer-Roca, C., Martínez-García, D., Segura, A., Gomis, O., Muñoz, A., Rodríguez-Hernández, P., López-Solano, L., Alconchel, S., Sapiña, F., 2010. High-pressure x-ray diffraction and ab initio study of $\text{Ni}_2\text{Mo}_3\text{N}$, $\text{Pd}_2\text{Mo}_3\text{N}$, $\text{Pt}_2\text{Mo}_3\text{N}$, $\text{Co}_3\text{Mo}_3\text{N}$, and $\text{Fe}_3\text{Mo}_3\text{N}$: Two families of ultra-incompressible bimetallic interstitial nitrides. *Phys. Rev. B* 82, 174105.
- [67] Zhang, C., Guo, S.P., Jiang, H., Zhong, G.H., Su, Y.H., 2015. Zero-point effects on phase transitions of thorium dihydride under high pressure. *J. Phys. Chem. C* 119, 13465–13471.
- [68] Li, X.F., Liu, H.Y., Peng, F., 2016. Crystal structures and superconductivity of technetium hydrides under pressure. *Phys. Chem. Chem. Phys.* 18, 28791–28796.
- [69] Zhuang, Q., Jin, X.L., Cui, T., Zhang, D., Li, Y., Li, X., Bao, K., Liu, B.B., 2018. Effect of electrons scattered by optical phonons on superconductivity in MH_3 ($M = \text{S}, \text{Ti}, \text{V}, \text{Se}$). *Phys. Rev. B* 98, 024514.
- [70] Zhuang, Q., Jin, X.L., Lv, Q.Q., Li, Y., Shao, Z.J., Liu, Z., Li, X., Zhang, H.D., Meng, X., Bao, K., Cui, T., 2017. Investigation of superconductivity in compressed vanadium hydrides. *Phys. Chem. Chem. Phys.* 19, 26280–26284.
- [71] Li, X., Peng, F., 2017. Superconductivity of pressure-stabilized vanadium hydrides. *Inorg. Chem.* 56, 13759–13765.
- [72] Zhang, H.D., Jin, X.L., Lv, Y.Z., Zhuang, Q., Liu, Y.X., Lv, Q.Q., Bao, K., Li, D., Liu, B.B., Cui, T., 2015. High-temperature superconductivity in compressed solid silane. *Sci. Rep.* 5, 8845.
- [73] Zhang, H.D., Jin, X.L., Lv, Y.Z., Zhuang, Q., Li, Y., Bao, K., Li, D., Liu, B.B., Cui, T., 2016. Pressure-induced phase transition of SnH_4 : a new layered structure. *RSC adv.* 6, 10456–10461.
- [74] Lonie, D.C., Hooper, J., Altintas, B., Zurek, E., 2013. Metallization of magnesium polyhydrides under pressure. *Phys. Rev. B* 87, 054107.
- [75] Fu, Y.H., Du, X.P., Zhang, L.J., Peng, F., Zhang, M., Pickard, C.J., Needs, R.J., Singh, D.J., Zheng, W.T., Ma, Y.M., 2016. High-pressure phase stability and superconductivity of pnictogen hydrides and chemical trends for compressed hydrides. *Chem. Mater.* 28, 1746–1755.
- [76] Liu, Y.X., Duan, D.F., Tian, F.B., Wang, C., Ma, Y.B., Li, D., Huang, X.L., Liu, B.B., Cui, T., 2016. Stability and properties of the RuH system at high pressure. *Phys. Chem. Chem. Phys.* 18, 1516–1520.
- [77] Du, M.Y., Zhang, Z.H., Song, H., Yu, H.Y., Cui, T., Kresin, V.Z., Duan, D.F., 2021. High-temperature superconductivity in transition metallic hydrides MH_{11} ($M = \text{Mo}, \text{W}, \text{Nb}$, and Ta) under high pressure. *Phys. Chem. Chem. Phys.* 23, 6717–6724.
- [78] Allen, P.B., Dynes, R.C., 1975. Transition temperature of strong-coupled superconductors reanalyzed. *Phys. Rev. B* 12, 905–922.
- [79] Zhang, J.Q., Jin, Y.Y., Zhang, C.Z., Wang, Y.Q., Tang, L.B., Li, S., Ju, M., Wang, J.J., Sun, W.G., Dou, X.L., 2022. The crystal structures, phase stabilities, electronic structures and bonding features of iridium borides from first-principles calculations. *RSC Adv.* 12, 11722–11731.
- [80] Sun, W., Kuang, X., Keen, H. D., Lu, C., Hermann, A., 2020. Second group of high-pressure high-temperature lanthanide polyhydride superconductors. *Phys. Rev. B* 102, 144524.
- [81] Zheng, J., Sun, W., Dou, X., Mao, A. J., Lu, C., 2021. Pressure-driven structural phase transitions and superconductivity of ternary hydride MgVH_6 . *J. Phys. Chem. C* 125, 3150–3156.
- [82] Li, S., Wang, H., Sun, W., Lu, C., Peng, F., 2022. Superconductivity in compressed ternary alkaline boron hydrides. *Phys. Rev. B*, 105, 224107.
- [83] Jin, Y. Y., Zhang, J. Q., Ling, S., Wang, Y. Q., Li, S., Kuang, F. G., Wu, Z. Y., Zhang, C. Z., 2022. Pressure-induced novel structure with graphene-like boron-layer in titanium monoboride. *Chin. Phys. B* 10.1088/1674-1056/ac9222.
- [84] Drozdov, A. P., Erements, M. I., Troyan, I. A., Ksenofontov, V., Shylin, S. I., 2015. Conventional superconductivity at 203 kelvin at high pressures in the sulfur hydride system. *Nature* 525, 73–76.
- [85] Duan, D., Liu, Y., Tian, F., Li, D., Huang, X., Zhao, Z., Yu, H., Liu, B., Tian, W., Cui, T., 2014. Pressure-induced metallization of dense $(\text{H}_2\text{S})_2\text{H}_2$ with high-Tc superconductivity. *Sci. Rep.* 4, 1–6.
- [86] Kim, D. Y., Scheicher, R. H., Ahuja, R., 2009. Predicted high-temperature superconducting state in the hydrogen-dense transition-metal hydride YH_3 at 40 K and 17.7 GPa. *Phys. Rev. Lett.* 103, 077002.
- [87] Gupta, M., 1982. Electronic properties and electron-phonon coupling in zirconium and niobium hydrides. *Phys. Rev. B* 25, 1027.
- [88] Kvashnin, A. G., Zakaryan, H. A., Zhao, C., Duan, Y., Kvashnina, Y. A., Xie, C., Oganov, A. R., 2018. New tungsten borides, their stability and outstanding mechanical properties. *J. Phys. Chem. Lett.* 9, 3470–3477.
- [89] Yan, X., Chen, Y., Xiang, S., Kuang, X., Bi, Y., Chen, H., 2016. High-temperature-and high-pressure-induced formation of the Laves-phase compound XeS_2 . *Phys. Rev. B* 93, 214112.
- [90] Rybkovskiy, D. V., Kvashnin, A. G., Kvashnina, Y. A., Oganov, A. R., 2020. Structure, stability, and mechanical properties of boron-rich Mo–B phases: a computational study. *J. Phys. Chem. Lett.* 11, 2393–2401.
- [91] Feng, X.L., Zhang, J.R., Gao, G.Y., Liu, H.Y., Wang, H., 2015. Compressed sodalite-like MgH_6 as a potential high-temperature superconductor. *RSC Adv.* 5, 59292–59296.
- [92] Jiang, H., Wang, W., Zhang, C., Hu, X.N., Zhong, G.H., Lu, X.Q., Su, Y.H., 2014. Phase transitions of actinium dihydride: Pressure-induced charge transfer driving effect. *Int. J. Hydrog. Energy* 39, 15827–15835.
- [93] Gao, G.Y., Wang, H., Zhu, L., Ma, Y.M., 2012. Pressure-induced formation of noble metal hydrides. *J. Phys. Chem. C* 116, 1995–2000.