Universal Fermi velocity in highly compressed hydride superconductors

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Abstract

Fermi velocity, \( v_F \), is one of the primary characteristics of any conductor, including superconductors. For conductors at ambient pressure several experimental techniques have been developed to measure \( v_F \) and, for instance, Zhou et al (Nature 423 398 (2003)) reported that high-\( T_c \) cuprates exhibit universal nodal Fermi velocity of \( v_{F,\text{univ}} = (2.7 \pm 0.5) \times 10^5 \, \text{m/s} \). However, there were no experimental techniques applied to measure \( v_F \) in highly compressed near-room-temperature superconductors (NRTS), due to experimental challenges. Here to answer a question about the existence of the universal Fermi velocity in NRTS materials, we analyzed full inventory of the ground-state upper critical field data, \( B_{c2}(0) \), for these materials and found that this class of superconductors exhibits universal Fermi velocity of \( v_{F,\text{univ}} = \frac{1}{1.3} \times \left( \frac{2\Delta(0)}{k_B T_c} \right) \times 10^5 \, \text{m/s} \) (where \( \Delta(0) \) is ground state amplitude of the energy gap). Due to the ratio of \( \frac{2\Delta(0)}{k_B T_c} \) is varying within a narrow range of \( 3.2 \leq \frac{2\Delta(0)}{k_B T_c} \leq 5 \), then \( v_{F,\text{univ}} \) in NRTS materials is in a range of \( 2.5 \times 10^5 \, \text{m/s} \leq v_{F,\text{univ}} \leq 3.8 \times 10^5 \, \text{m/s} \), which is in the same ballpark with its high-\( T_c \) cuprates counterpart.
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I. Introduction

Since pivotal experimental discovery of first near-room-temperature superconductor (NRTS) \( \text{H}_3\text{S} \) by Drozdov \textit{et al} [1], nearly two dozen of highly compressed hydrogen-rich superconducting phases have been synthesized in binary and ternary systems [2-17]. Experimental studies of NRTS are well supported by first-principles calculations [18-30], however, experimental characterizations of NRTS phases are limited by narrow set of techniques, which can be applied for materials inside of diamond anvil cell (DAC) [25-27]. These techniques are X-ray diffraction (XRD) phase analysis, Raman spectroscopy and magnetoresistance measurements [31-35]. In some advanced experiments, Hall effect measurements can be also performed [31]. Based on this, only two characteristic values of the superconducting state of the NRTS phases are commonly extracted from the experimental data, which are the transition temperature, \( T_c \), and the extrapolated value for the ground state upper critical field, \( B_{c2}(0) \) or the ground state superconducting coherence length, \( \xi(0) \), which can be derived from the Ginzburg-Landau [36] expression:

\[
\xi(0) = \sqrt{\frac{\phi_0}{2\pi B_{c2}(0)}}
\]

(1)

where \( \phi_0 = \frac{\hbar}{2e} \) is the superconducting flux quantum, \( \hbar \) is Planck constant and \( e \) is electron electric charge.

Other important parameters of the NRTS materials, from which we can mention the Fermi velocity, \( v_F \), cannot be measured to date, due to challenging experimental problems associated with measurement of this value for samples inside of DAC. However, considering that all NRTS superconductors are hydrides, there is an expectation, that these materials can exhibit universal Fermi velocity, \( v_{F,\text{univ}} \), as the one was discovered in cuprates, \( v_{F,\text{univ}} = \)}
(2.7 ± 0.5) \times 10^5 \frac{m}{s} \) (which was reported by Zhou et al [37]). In Figure 1 we showed the dataset reported by Zhou et al [37].

**Figure 1.** Universal nodal Fermi velocity, \( v_{F,\text{univ}} = (2.7 \pm 0.5) \times 10^5 \frac{m}{s} \), for cuprate superconductors. Raw data reported by Zhou et al [37]. Data presented for (La\(_{2-x}\)Sr\(_x\))CuO\(_4\) (LSCO), (La\(_{2-x}\)Nd\(_y\)Sr\(_x\))CuO\(_4\) (Nd-LSCO), Bi\(_2\)Sr\(_2\)CaCu\(_2\)O\(_8\) (Bi-2212), Bi\(_2\)Sr\(_2\)CuO\(_6\) (Bi-2201), (Ca\(_{2-x}\)Na\(_x\))CuO\(_2\)Cl\(_2\) (Na-CCOC), and Tl\(_2\)Ba\(_2\)CuO\(_6\) (Tl-2201).

Partial theoretical background for the quest for universal Fermi velocity in NRTS is based from one hand on recent understanding [38] that sulphur in H\(_3\)S is an analogue to the oxygen in cuprates, and from other hand that highly compressed hydrides are nicely added in main global scaling laws for superconductors [39-42].

Here, we reported the result of our search for universal Fermi velocity in NRTS materials which was based on the analysis of full inventory of the ground state upper critical field, \( B_{c2}(0) \) in these materials. In the result, we found that universal Fermi velocity, \( v_{F,\text{univ}} \), does exist in NRTS materials, and the one obeys the empirical law:

\[
v_{F,\text{univ}} = \frac{1}{1.3} \times \frac{\Delta(0)}{k_B T_c} \times 10^5 \left( \frac{m}{s} \right)\]  

(2)
where \( k_B \) is the Boltzmann constant, and \( \Delta(0) \) is the ground state superconducting energy gap.

II. Approach description

In Bardeen-Cooper-Schrieffer (BCS) theory of superconductivity \([43]\) the ground state coherence length, \( \xi(0) \), and the amplitude of the ground state energy gap, \( \Delta(0) \), are linked through the expression:

\[
\xi(0) = \frac{\hbar v_F}{\pi \Delta(0)}
\]  

(3)

where \( \hbar \) is reduced Planck constant. BCS theory also has a dimensionless ratio:

\[
\alpha = \frac{2\Delta(0)}{k_B T_c}
\]  

(4)

By substituting Eqs. 3,4 in Eq. 1, one can get a dependence of the ground state upper critical field vs the transition temperature:

\[
B_{c2}(0) = \left[ \frac{\pi \phi_0 k_B^2}{\hbar} \right] \times \frac{\alpha^2}{v_F^2} \times T_c^2
\]  

(5)

where the multiplicative pre-factor in square brackets is a constant:

\[
A = \left[ \frac{\pi \phi_0 k_B^2}{\hbar} \right] = 1.38 \times 10^7 \frac{T \times m^2}{s^2 \times K^2}
\]  

(6)

Thus, if hydrogen-rich superconductors exhibit universal Fermi velocity, \( v_{F,\text{univ}} \), the fit of full inventory of \( B_{c2}(0) \) vs \( T_c \) dataset to the equation of:

\[
B_{c2}(0) = A \times f \times T_c^\beta
\]  

(7)

where \( \beta \) and \( f = \frac{\alpha^2}{v_F^2} \) are free fitting parameters, should reveal that:

\[
\beta \cong 2
\]  

(8)

and if this is a case, then universal Fermi velocity, \( v_{F,\text{univ}} \), can be calculated from deduced free-fitting parameter \( f \):

\[
v_{F,\text{univ}} = \frac{\alpha}{\sqrt{f}} = \frac{1}{\sqrt{f}} \times \frac{2\Delta(0)}{k_B T_c}
\]  

(9)
It should be noted, that \(\alpha = \frac{2\Delta(0)}{k_B T_c}\) in highly-compressed hydrogen-rich superconductors is varying within a range \([8,12,27,42,44-48]\):

\[
3.2 \leq \frac{2\Delta(0)}{k_B T_c} \leq 5
\]

(10)

(where the lower limit is the value deduced from experiment [42,44,48], while the upper limit is based on many results reported by the first-principles calculations, which always predict \(4.3 \leq \frac{2\Delta(0)}{k_B T_c}\) \([8,12,27,45-47]\) in NRTS materials).

### III. Extrapolation model for the ground state upper critical field

Eq. 7 has the ground state upper critical field, \(B_{c2}(0)\), as dependent variable. However, it is important to note that this value can be determined by the use of extrapolative models [49-53] which use experimental \(B_{c2}(T)\) data measured at high reduced temperatures, \(\frac{T}{T_c}\). Primary reason, why there is a necessity for extrapolative models, is that all highly-compressed hydrogen-rich superconductors have \(B_{c2}(T \to 0 \text{ K}) > 20 \text{ T}\), which cannot be measured by conventional PPMS systems (manufactured by Quantum Design) where the highest magnetic field is limited by \(B_{\text{appl}} = 9-16 \text{ Tesla}\) (depends on the model). It should be also stressed, that \(B_{c2}(T \to 0 \text{ K})\) for NRTS compounds of H$_2$S, LaH$_{10}$, YH$_6$/YH$_9$ and (La,Y)H$_{10}$ are so high, that even experimental data measured at world-top quasi-DC magnetic field facility [31,54] only covers the range of reduced temperatures \(\frac{1}{2} \leq \frac{T}{T_c}\).

From several available extrapolative \(B_{c2}(T)\) models [49-53] in this paper we used analytical approximative expression for Werthamer-Helfand-Hohenberg (WHH) theory [55,56], which was proposed by Baumgartner et al [53] (and, thus, Eq. 11 we will designate as B-WHH model):

\[
B_{c2}(T) = \frac{1}{0.693} \times \frac{\phi_0}{2\pi \xi^2(0)} \times \left( (1 - \frac{T}{T_c}) - 0.153 \times (1 - \frac{T}{T_c})^2 - 0.152 \times (1 - \frac{T}{T_c})^4 \right)
\]

(11)
where \( \xi(0) \) and \( T_c = T_c(B=0) \) are two free fitting parameters. Eq. 11 [53] was initially proposed to extrapolate \( B_{c2}(T) \) data for neutron-irradiated Nb₃Sn alloys, and recently several research groups found that Eq. 11 is a good approximated tool for a variety of superconducting materials [4,57-62]. Based on this, in current study we used Eq. 11 as a good, robust and simple analytical tool to extrapolate \( B_{c2}(T) \) curve on low temperature/high field region [4,57-62], because, as we mentioned above, \( B_{c2}(T) \) datasets for NRTS superconductors are measured only at high reduced temperatures, \( \frac{1}{2} \leq \frac{T}{T_c} \), because of experimental limitations.

There is a need to describe the criterion to extracting \( B_{c2}(T) \) datasets from experimentally measured \( R(T,B_{\text{appl}}) \) curves. There are several criteria for the \( T_c, B_{c2}(T) \) and \( T_c(B_{\text{appl}}) \) definition, which for the case of NRTS discussed recently in Ref. 63. In the result we found [63,64] that the best match between the electron-phonon coupling constant \( \lambda_{\text{e-ph}} \) extracted from \( R(T,B_{\text{appl}}=0) \) curves and \( \lambda_{\text{e-ph}} \) computed by first principles calculation is when \( T_c \) is defining at as low as practically possible fraction of \( R(T)/R_{\text{norm}} \) (where \( R_{\text{norm}} \) is the normal state resistance just above the transition). By analysing full inventory of \( R(T,B_{\text{appl}}) \) data for NRTS materials herein, we came to conclusion that due to noise/slope issues of real-world \( R(T,B_{\text{appl}}) \) curves and a fact that highly-compressed superhydrides contained several superconducting phases the appropriate criterion, which we used in this study is:

\[
\frac{R(T,B_{\text{appl}})}{R(T_{\text{onset}},B_{\text{appl}})} = 0.05
\]

IV. Results

4.1. Unannealed highly-compressed sulphur hydride

In the first paper on NRTS superconductors, Drozdov et al [1] reported \( R(T,B_{\text{appl}}) \) data for unannealed highly-compressed sulphur hydride (\( P = 155 \) GPa) in their Figure 3(a). By using
the criterion of Eq. 12 (which is \( R(T, B_{app}) \) criterion = 23 mΩ for given \( R(T, B_{app}) \) curves showed in bottom insert in Figure 3(a) in Ref. 1), we extracted \( B_{c2}(T) \) dataset for this sample, which is shown in Fig. 2. Because this \( B_{c2}(T) \) dataset covers significant part of full temperature range, \( 0 K < T \leq T_c \), there was no need to use extrapolative fit and instead we fitted this dataset to the model [48], which allows to deduce \( \Delta(0), \frac{2\Delta(0)}{k_B T_c}, \Delta C/C \) (which is the relative jump in electronic specific heat at \( T_c \)):

\[
B_{c2}(T) = \phi_0 \frac{2\pi \xi^2(0)}{2} \times \left( \frac{1.77 - 0.43 \left( \frac{T}{T_c} \right)^2 + 0.07 \left( \frac{T}{T_c} \right)^4}{1.77} \right)^2 \times \left[ 1 - \frac{1}{2k_B T} \int_0^\infty \frac{d\epsilon}{\cosh^2 \left( \frac{\sqrt{\epsilon^2 + \Delta^2(T)}}{2k_B T} \right)} \right] \]

(13)

where temperature dependent superconducting gap, \( \Delta(T) \), is given by [65,66]:

\[
\Delta(T) = \Delta(0) \times \tanh \left[ \frac{\pi k_B T_c}{\Delta(0)} \times \sqrt{\frac{\eta \times \frac{\Delta C}{c}}{c} \times \left( \frac{T_c}{T} - 1 \right)} \right] \]

(14)

where \( \eta = 2/3 \) for \( s \)-wave superconductors.

Eqs. 13,14 were used to extract \( \xi(0), \Delta(0), T_c \) and \( \frac{\Delta C}{c} \) from \( B_{c2}(T) \) datasets in a variety of superconductors, for instance, for two highly-compressed hydrides phases of H\(_3\)S [48] and of SnH\(_{12} \) [42], V\(_3\)Si [67], and several iron-based superconductors [67]. However, it should be stressed that the approach (i.e. Eq. 13,14) is only applicable for \( B_{c2}(T) \) datasets defined by Eq. 12 or by stricter criterion.
Figure 2. The upper critical field data, $B_{c2}(T)$, and data fit to Eqs. 13,14 for unanneled highly-compressed sulphur hydride ($P = 190$ GPa). Raw $R(T,B_{appl})$ dataset reported by Drozdov et al [1]. Deduced values are shown in the figure. 95% confidence bands are shown by a pink shaded area. Fit quality is $R = 0.9985$.

One of the most important deduced parameters, $\alpha = \frac{2\Delta(0)}{k_B T_c} = 3.2 \pm 0.3$, is in remarkable agreement with counterpart values deduced for highly-compressed annealed H$_3$S ($P = 155$-160 GPa), $\frac{2\Delta(0)}{k_B T_c} = 3.20 \pm 0.02$ [44] and $\frac{2\Delta(0)}{k_B T_c} = 3.55 \pm 0.31$ [48], and for highly-compressed annealed SnH$_{12}$ ($P = 190$ GPa), $\frac{2\Delta(0)}{k_B T_c} = 3.28 \pm 0.18$ [42]. Deduced $\frac{\Delta C}{C} = 0.7 \pm 0.1$ is also below the weak-coupling limit of BCS theory $\frac{\Delta C}{C} = 1.43$, as its counterpart in the annealed H$_3$S material, $\frac{\Delta C}{C} = 1.2 \pm 0.3$ [48]. It should be mentioned that to deduce $\frac{\Delta C}{C}$ with higher accuracy requires more $B_{c2}(T)$ datapoints, especially at $T \sim T_c$. Deduced $B_{c2}(0)$ and $T_c$ are included in Table I.

4.2. Annealed highly-compressed hydrides

Reported $R(T,B_{appl})$ datasets for several annealed highly-compressed hydrides were processed by utilizing Eq. 12 to extract $B_{c2}(T)$ datasets. Obtained datasets were fitted to Eq. 11 and deduced values included in Table I. These materials are:
1. Sulphur superhydride, H\textsubscript{3}S ($P = 155, 160$ GPa), for which raw data reported by Mozaffari et al [31]. Fits are shown in Figure S1.

2. Cerium superhydride, CeH\textsubscript{n} ($P = 88, 137, 139$ GPa), for which raw data reported by Chen et al [12]. Fits are shown in Figure S2.

3. Lanthanum superhydride, LaH\textsubscript{10} ($P = 120, 136$ GPa), for which raw data reported by Sun et al [54]. Fits are shown in Figure S3.

4. Yttrium superhydride/superdeiteride, YH\textsubscript{6}/YD\textsubscript{6} ($P = 172, 200$ GPa), for which raw data reported by Troyan et al [4]. Fits are shown in Figure S4.

5. Lanthanum-yttrium superhydride, (La,Y)H\textsubscript{10} ($P = 182, 183, 186$ GPa), for which raw data reported by Semenok et al [8]. Fits are shown in Figure S5.

6. Tin superhydride, SnH\textsubscript{12} ($P = 190$ GPa), for which raw data reported by Hong et al [11]. Fits are shown in Figure S6.

7. Thorium superhydrides, ThH\textsubscript{9} and ThH\textsubscript{10} ($P = 170$ GPa), for which raw data reported by Semenok et al [16]. Fits are shown in Figure S7.

### 4.3. Analysis of $B_{c2}(0)$ vs $T_c$ for superhydride phases

All deduced $B_{c2}(0)$ and $T_c$ values for superhydride phases are collected in Table I, where we also added data for Th\textsubscript{4}H\textsubscript{15} phase reported by Satterthwaite and Toepke [68].

| Phase and Data Source | Figure No. | Pressure (GPa) | $T_c$ (K) | $\Delta T_c$ (K) | $B_{c2}(0)$ (T) | $\Delta B_{c2}(0)$ (T) |
|----------------------|------------|----------------|----------|-----------------|----------------|----------------------|
| Unannealed sulphur hydride (Fig. 3(a) in Ref. 1) | 1 | 155 | 13.9 | 0.3 | 6.3 | 0.4 |
| Annealed H\textsubscript{3}S (Fig. 3 in Ref. 31) | 2(a) | 155 | 185 | 2 | 98.8 | 1.2 |
| Annealed H\textsubscript{3}S (Figs. S1,S2 in Ref. 31) | 2(b) | 155 | 196.1 | 0.6 | 71.1 | 1.1 |
| Annealed H\textsubscript{3}S (Fig. 3 in Ref. 31) | 2(c) | 160 | 143.9 | 1.4 | 59.2 | 2.3 |
| Annealed CeH\textsubscript{9} (Fig. 3(a) in Ref. 12) cooling | 3(a) | 88 | 38.8 | 0.4 | 16.5 | 1 |
| Annealed CeH\textsubscript{9} (Fig. 1(c) in Ref. 12) warming | 3(b) | 139 | 88.6 | 0.3 | 22.2 | 0.7 |
| Annealed CeH\textsubscript{9} (Fig. 1(d) in Ref. 12) cooling | 3(c) | 137 | 81.9 | 0.7 | 18.4 | 0.7 |
| Annealed CeH\textsubscript{9} (Fig. 1(d) in Ref. 12) warming | 3(d) | 137 | 82.7 | 0.7 | 18.7 | 0.6 |
| Annealed LaH\textsubscript{10} (Fig. 3(a) in Ref. 47) | 4(a) | 120 | 174.8 | 0.8 | 90 | 3 |
Annealed LaH$_{10}$ (Fig. 3(b) in Ref. 47) & 4(b) & 136 & 206.2 & 0.8 & 136 & 3  
Annealed YD$_{6}$ (Fig. S13(a) in Ref. 4) & 5(a) & 172 & 157.7 & 0.2 & 124.9 & 2.4  
Annealed YH$_{6}$ (Fig. S16(c) in Ref. 4) & 5(b) & 200 & 206.2 & 0.2 & 97.2 & 1.4  
Annealed (La,Y)H$_{10}$ (Fig. S27(b) in Ref. 8) & 6(a) & 183 & 203.5 & 0.2 & 101.6 & 1.8  
Annealed (La,Y)H$_{10}$ (Fig. S28(a) in Ref. 8) & 6(b) & 182 & 234 & 0.1 & 135.8 & 1.5  
Annealed (La,Y)H$_{10}$ (Fig. S28(a) in Ref. 8) & 6(c) & 186 & 234.5 & 0.1 & 134 & 1  
Annealed SnH$_{12}$ (Fig. 4(a) in Ref. 11) cooling & 7(a) & 190 & 62.8 & 0.4 & 9 & 0.2  
Annealed SnH$_{12}$ (Fig. 4(a) in Ref. 11) warming & 7(b) & 190 & 64.1 & 0.5 & 8.9 & 0.2  
Annealed ThH$_{6}$ (Fig. 4(a) in Ref. 16) & 8(a) & 170 & 151.2 & 1.5 & 32 & 0.9  
Annealed ThH$_{10}$ (Fig. 4(a) in Ref. 16) & 8(b) & 170 & 150.6 & 0.4 & 43.4 & 0.6  
Th$_{4}$H$_{15}$ (Ref. 68) & ambient & 8.2 & 0.15 & 2.75 & 0.25  

Full dataset from Table I is shown in Figure 3 together with the fit to Eq. 7. Despite a fact that this dataset has a large scattering, it can be seen in Figure 3(a), that free-fitting power-law exponent, $\beta = 2.07 \pm 0.14$, is practically undistinguishable from expected $\beta \equiv 2$ value (Eq. 5). For the case when $\beta$ is free-fitting parameter (Figure 9(a)), deduced $f = (1.19 \pm 0.90) \times 10^{-10} \frac{s^2}{m^2}$ has a large uncertainty. However, when $\beta$ is fixed to 2 (Figure 3(b)), free-fitting parameter $f$ can be deduced with high accuracy:

$$ f = \frac{a^2}{v_{F,univ}^2} = (1.68 \pm 0.08) \times 10^{-10} \frac{s^2}{m^2} $$

(15)

From Equation 15, one can obtain:

$$ v_{F,univ} = \frac{a}{(1.30 \pm 0.03) \times 10^5 \frac{m}{s}} \approx \frac{1}{1.3} \times \frac{2\Delta(0)}{k_B T_c} \times 10^5 \frac{m}{s} $$

$$ 2.5 \times 10^5 \frac{m}{s} \lesssim v_{F,univ} \lesssim 3.8 \times 10^5 \frac{m}{s} $$
Figure 3. Total $B_{c2}(0)$ vs $T_c$ dataset for hydrogen-rich superconductors deduced in this work (Table I) and data fit to (a) Eq. 7 and (b) Eq. 5. (a) – free-fitting $\beta = 2.07 \pm 0.14$ and $f = (1.19 \pm 0.90) \times 10^{-10} \frac{s^2}{m^2}$, fit quality is $R = 0.9361$. (b) – $\beta = 2.0$ (fixed) and free-fitting $(1.68 \pm 0.08) \times 10^{-10} \frac{s^2}{m^2}$, fit quality is $R = 0.9354$.

Deduced $v_{F,univ}$ for hydrogen-rich superconductors (Eq. 16) is at the same ballpark as its counterpart for high-$T_c$ cuprates $v_{F,univ} = (2.7 \pm 0.5) \times 10^5 \frac{m}{s}$ [37], if one takes into account Eq. 10.

V. Conclusions

In this study we proposed that hydrogen-rich superconductors, including near-room-temperature superconductors, form distinguished subclass of superconducting materials, which exhibits universal Fermi velocity, $v_F$, which is given by empirical expression of:
\[ v_{F,\text{univ}} = \frac{1}{1.3} \times \frac{2\Delta(0)}{k_B T_c} \times 10^5 \text{ m/s}. \]

Considering that the gap-to-transition temperature ratio is varying within \( \frac{2\Delta(0)}{k_B T_c} \)

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**Data Availability Statement**

No new data were created or analysed in this study. Data sharing is not applicable to this article.

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SUPPLEMENTARY INFORMATION

Universal Fermi velocity in highly compressed hydride superconductors

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S1. Annealed highly-compressed sulphur hydride

Raw $R(T,B_{\text{appl}})$ datasets for annealed highly-compressed sulphur hydride ($P = 155, 160$ GPa) reported by Mozaffari et al [31] were processed and fitted to Eq. 11. Deduced $B_{c2}(0)$ and $T_c$ values are included in Table I.

![Figure S1](Image)

**Figure S1.** The upper critical field, $B_{c2}(T)$, data for highly-compressed $Im\bar{3}m$-$H_3S$ phase at $P = 155$ GPa (a,b) and $P = 160$ GPa (c) and data fit to B-WHH model [53] (Eq. 11). Raw $R(T,B_{\text{appl}})$ datasets reported by Mozaffari et al [31]. Fits quality are (a) $R = 0.9892$; (b) $R = 0.9974$; (c) $R = 0.9837$. 95% confidence bands are shown by pink shaded areas.
S2. Annealed highly-compressed cerium hydride

Chen et al [12] reported on the observation high-temperature superconductivity in superhydrides of cerium. By using the criterion of Eq. 12, we extracted $B_{c2}(T)$ datasets from four $R(T,B_{appl})$ curves reported by Chen et al [12] and fitted these $B_{c2}(T)$ datasets to Eq. 11 in Figure S2.

Figure S2. The upper critical field, $B_{c2}(T)$, data for highly-compressed superhydrides of cerium and data fits to Eq. 11. Raw $R(T,B_{appl})$ datasets reported by Chen et al [12]. (a) Raw $R(T,B_{appl})$ data reported in Fig. S7(a) [12], fit quality is $R = 0.9792$. (b) Raw $R(T,B_{appl})$ data reported in Fig. 1(c) [12], fit quality is $R = 0.9966$. (c,d) Raw $R(T,B_{appl})$ data reported in Fig. 1(d) [12], fit quality is $R = 0.9860$ (c) and $R = 0.9859$ (d). 95% confidence bands are shown by pink shaded areas.
S3. Annealed highly-compressed cerium hydride

Sun et al [54] reported results of magnetoresistance studies for two phases of highly-compressed LaH$_{10}$. By using the criterion of Eq. 12, we extracted $B_{c2}(T)$ datasets for these two phases and fitted these $B_{c2}(T)$ datasets to B-WHH model (Eq. 11) in Figure 4. Deduced $B_{c2}(0)$ and $T_c$ values are included in Table I.

Figure S3. The upper critical field, $B_{c2}(T)$, data for highly-compressed LaH$_{10}$ and data fits to Eq. 11. Raw $R(T,B_{appl})$ datasets reported by Sun et al [54]. (a) Raw $R(T,B_{appl})$ data reported in Fig. 3(a) [54], fit quality is $R = 0.9907$. (b) Raw $R(T,B_{appl})$ data reported in Fig. 3(b) [54], fit quality is $R = 0.9941$. 95% confidence bands are shown by pink shaded areas.
S4. Annealed highly-compressed YH₆/YD₆

Recently, Troyan et al [4] and Kong et al [5] reported on the discovery of new highly-compressed NRTS polyhydrides/polydeuterides of yttrium, YH₆/YD₆ (n = 4,6,7,9). Here in Figure 5 we showed extracted $B_{c2}(T)$ for YD₆ ($P = 172$ GPa, raw $R(T,B_{appl})$ dataset is from Figure S13(a) [4]) and for YH₆ ($P = 200$ GPa, raw $R(T,B_{appl})$ dataset is from Figure S16(a) [4]) and data fits to B-WHH model (Eq. 11). Deduced $B_{c2}(0)$ and $T_c$ are included in Table I.

**Figure S4.** The upper critical field, $B_{c2}(T)$, data for highly-compressed YH₆/YD₆ and fits to Eq. 11. Raw $R(T,B_{appl})$ datasets reported by Troyan et al [4]. (a) Raw $R(T,B_{appl})$ data reported in Fig. S13(a) [4], fit quality is $R = 0.9971$. (b) Raw $R(T,B_{appl})$ data reported in Fig. S16(a) [4], fit quality is $R = 0.9982$. 95% confidence bands are shown by pink shaded areas.
S5. Annealed highly-compressed ternary \((\text{La,Y})\text{H}_{10}\)

Semenok et al [8] reported on the discovery of new ternary NRTS polyhydride of \((\text{Y,La})\text{H}_{10}\). In Figure 6 we showed extracted \(B_{c2}(T)\) datasets for \((\text{Y,La})\text{H}_{10}\) phase and data fits to B-WHH model (Eq. 11). Deduced \(B_{c2}(0)\) and \(T_c\) for this phase are included in Table I.

![Graphs showing \(B_{c2}(T)\) for \((\text{La,Y})\text{H}_{10}\) phases](image)

**Figure S5.** The upper critical field, \(B_{c2}(T)\), data for highly-compressed \((\text{La,Y})\text{H}_{10}\) and fits to Eq. 11. Raw \(R(T,B_{\text{appl}})\) datasets reported by Semenok et al [8]. (a) Raw \(R(T,B_{\text{appl}})\) data reported in Fig. S27(b) [8], fit quality is \(R = 0.9975\). (b) Raw \(R(T,B_{\text{appl}})\) data reported in Fig. S28(a) [8], fit quality is \(R = 0.9991\). (c) Raw \(R(T,B_{\text{appl}})\) data reported in Fig. S28(a) [8], fit quality is \(R = 0.9995\). 95% confidence bands are shown by pink shaded areas.
S6. Annealed highly-compressed SnH\textsubscript{12}

Recently, Hong et al [11] reported on the discovery of a new superconducting polyhydride of $C2/m$-SnH\textsubscript{12} ($P = 190$ GPa). Extracted $B_{c2}(T)$ datasets for this phase we already reported in our previous work (Table I in Ref. 41). Here in Figure 7 we fitted these datasets to B-WHH model (Eq. 11). Deduced $B_{c2}(0)$ and $T_c$ for this phase are included in Table I.

**Figure S6.** The upper critical field data, $B_{c2}(T)$, and data fit to Eq. 11 for $C2/m$-SnH\textsubscript{12} ($P = 190$ GPa). Raw $R(T,B_{appl})$ datasets reported by Hong et al [11] and extracted $B_{c2}(T)$ datasets can be found in Table I in Ref. 41. (a) fit quality is $R = 0.9971$; (b) fit quality is $R = 0.9978$. 

$T_c = 62.8 \pm 0.4$ K  
$B_{c2}(0) = 9.0 \pm 0.2$ T

$T_c = 64.1 \pm 0.5$ K  
$B_{c2}(0) = 8.9 \pm 0.2$ T
S7. Annealed highly-compressed ThH₉ and ThH₁₀

Semenok et al [16] reported on the discovery of a new NRTS polyhydrides of thorium, ThH₉ and ThH₁₀. Raw $R(T, B_{appl})$ dataset for mixture of ThH₉ and ThH₁₀ phases is in Figure 5(c) in Ref. [16]. To deduce $B_{c2}(T)$ dataset for phase ThH₁₀ we used the criterion of $R(T, B_{appl})_{\text{criterion}} = 4.9 \text{ m}\Omega$, while to deduce $B_{c2}(T)$ dataset for phase ThH₉ we used the criterion of $R(T, B_{appl})_{\text{criterion}} = 0.46 \text{ m}\Omega$. In Figure 7 we fitted these datasets to B-WHH model (Eq. 11). Deduced $B_{c2}(0)$ and $T_c$ for this phase are included in Table I.

![Graph](image)

**Figure S7.** The upper critical field data, $B_{c2}(T)$, and data fit to Eq. 11 for NRTS phases of (a) ThH₉ and (b) ThH₁₀. Raw $R(T, B_{appl})$ datasets reported by Semenok et al [16] in their Figure 5(c). (a) fit quality is $R = 0.9866$; (b) fit quality is $R = 0.9957$. 
