Classifying superconductivity in compressed H_3S

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Abstract

The discovery of high-temperature superconductivity in compressed H_3S by Drozdov and co-workers (A. Drozdov, et. al., *Nature* ***525***, 73 (2015)) heralded a new era in superconductivity. To date, the record transition temperature of T_c = 260 K stands with another hydrogen-rich compound, LaH_{10} (M. Somayazulu, et. al., arXiv:1808.07695) which becomes superconducting at pressure of P = 190 GPa. Despite very intensive first-principle theoretical studies of hydrogen-rich compounds compressed to megabar level pressure, there is a very limited experimental dataset available for such materials. In this paper, we analyze the upper critical field, B_{c2}(T), data of highly compressed H_3S reported by Mozaffari and co-workers (S. Mozaffari, et. al., *LA-UR*-18-30460, DOI: 10.2172/1481108) by utilizing four different models of $B_{c2}(T)$. In result, we find that the ratio of superconducting energy gap, $\Delta(0)$, to the Fermi energy, ε_F, in all considered scenarios is $0.03 < \Delta(0)/\varepsilon_F < 0.07$, with respective ratio of T_c to the Fermi temperature, T_F, $0.012 < T_c/T_F < 0.039$. These characterize H_3S as unconventional superconductor and places it on the same trend line in T_c versus T_F plot, where all unconventional superconductors located.

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I. Introduction

Experimental discovery a superconductivity above T = 200 K in highly compressed H_3S by Drozdov et al [1] is one of the most fascinating confirmation of the Bardeen-Cooper-Schrieffer (BCS) theory [2] and the phonon-mediated pairing scenario which can sustain superconductivity at such high temperature [3,4]. Moreover, recent experimental results on another hydrogen-rich compound of LaH_{10} [5,6], further showed that BCS electron-phonon pairing mechanism works at much higher temperatures, and highest observed in experiment superconducting transition temperature, T_c, for LaH_{10} compound is T_c = 260 K [6]. Historical aspects of the discovery, included the astonishing theoretical prediction of Ashcroft [7], and reviews of theoretical works in the field can be found elsewhere [8-13].

Most theoretical works [10,12,13-18] came to conclusion that H_3S is strong coupled superconductor with BCS ratio:

$$\frac{2\cdot\Delta(0)}{k_B\cdot T_c} = \alpha = 4.5 - 4.7 \tag{1}$$

where $\Delta(0)$ is ground state of the superconducting energy gap, k_B is the Boltzmann constant. In contrast to this, our analysis [19] of experimental self-field critical current density, $J_c(sf,T)$ (reported by Drozdov and co-workers in [1]), showed that the BCS ratio (Eq. 1) for H_3S is more likely to be very close to the weak-coupling limit of 3.53, and we deduced value for $\Delta(0)$ = 28 meV [19,20], while many theoretical works came to predicted values in the range of $\Delta(0)$ = 40-45 meV. Modern spectroscopic techniques have been applied to H_3S [21], which confirmed theoretically calculated energy spectrum for energies above 70 meV.

In this paper, we analyse recently released experimental upper critical field, $B_{c2}(T)$, data [22] for highly compressed H_3S with the purpose to deduce the Fermi velocity, v_F, and Fermi energy, ε_F, for this material.

II. Description of models

In the Ginzburg-Landau theory, the upper critical field is given by following expression:

$$B_{c2}(T) = \frac{\phi_0}{2 \cdot \pi \cdot \xi^2(T)} \tag{2}$$

where $\phi_0 = 2.07 \cdot 10^{-15}$ Wb is flux quantum, and $\xi(T)$ is the coherence length. There is a well-known BCS expression [2]:

$$\xi(0) = \frac{\hbar \cdot v_F}{\pi \cdot \Delta(0)} \tag{3}$$

where $\hbar = h/2\pi$ is reduced Planck constant, and v_F is the Fermi velocity. Thus, from deduced $B_{c2}(0)$ and T_c and assumed α (Eq. 1), one can calculate the Fermi velocity, v_F:

$$v_F = \frac{\pi}{2} \cdot \xi(0) \cdot \frac{\alpha \cdot k_B \cdot T_c}{\hbar}, \tag{4}$$

the Fermi energy, ε_F:

$$\varepsilon_F = \frac{m_{eff}^* \cdot v_F^2}{2} \tag{5}$$

where m_{eff}^* is effective mass (for H_3S we used $m_{eff}^* = 2.76\ m_e$ [10]), and the Fermi temperature, T_F:

$$T_F = \frac{\varepsilon_F}{k_B} \tag{6}$$

where k_B is Boltzmann constant.

One of conventional models to analyse $B_{c2}(T)$ was given by Werthamer-Helfand-Hohenberg (WHH) [23,24]:

$$ln\left(\frac{T}{T_c(B=0)}\right) = \psi\left(\frac{1}{2}\right) - \psi\left(\frac{1}{2} + \frac{\hbar \cdot D \cdot B_{c2}(T)}{2 \cdot \phi_0 \cdot k_B \cdot T}\right) \tag{6}$$

where D is the diffusion constant of the normal conducting electrons/holes, with two free fitting parameters of $T_c(B=0)$ and D. Baumgartner *et al* [25] proposed simple and accurate analytical expression for $B_{c2}(T)$ within WHH model:

$$B_{c2}(T) = \frac{1}{0.693} \cdot \frac{\phi_0}{2 \cdot \pi \cdot \xi^2(0)} \cdot \left(\left(1 - \frac{T}{T_c}\right) - 0.153 \cdot \left(1 - \frac{T}{T_c}\right)^2 - 0.152 \cdot \left(1 - \frac{T}{T_c}\right)^4\right) \tag{7}$$

where ξ(0) and $T_c \equiv T_c(B=0)$ are two free fitting parameters. We will designate this model as B-WHH.

In addition, there are several analytical expressions which are in a wide use too [26-28]. For instance, there are classical two-fluid Gorter-Casimir model [29]:

$$B_{c2}(T) = \frac{\phi_0}{2\cdot\pi\cdot\xi^2(0)}\cdot\left(1-\left(\frac{T}{T_c}\right)^2\right) \quad (8)$$

and Jones-Hulm-Chandrasekhar (JHC) model [30]:

$$B_{c2}(T) = \frac{\phi_0}{2\cdot\pi\cdot\xi^2(0)}\cdot\left(\frac{1-\left(\frac{T}{T_c}\right)^2}{1+\left(\frac{T}{T_c}\right)^2}\right) \quad (9)$$

There is also a little-known equation from Gor'kov for $B_{c2}(T)$ [31] which was referred by Gor'kov as a good analytical interpolative approximation over the whole temperature range:

$$B_{c2}(T) = B_c(T)\cdot\frac{\sqrt{2}}{1.77}\cdot\frac{\lambda(0)}{\xi(0)}\cdot\left(1.77-0.43\cdot\left(\frac{T}{T_c}\right)^2+0.07\cdot\left(\frac{T}{T_c}\right)^4\right) \quad (10)$$

where $B_c(T)$ is the thermodynamic critical field, and λ(0) is the ground state London penetration depth. Eq. 8 was re-written by Jones *et al* [30] in following form:

$$B_{c2}(T) = \frac{1}{1.77}\cdot\frac{\phi_0}{2\cdot\pi\cdot\xi^2(0)}\cdot\left(1.77-0.43\cdot\left(\frac{T}{T_c}\right)^2+0.07\cdot\left(\frac{T}{T_c}\right)^4\right)\cdot\left(1-\left(\frac{T}{T_c}\right)^2\right) \quad (11)$$

We will designate Eq. 9 as G model.

In this paper, we utilise Eq. 8 in a different way. If we take in account, the Ginzburg-Landau (GL) theory expressions:

$$B_{c2}(T) = \sqrt{2}\cdot\frac{\lambda(T)}{\xi(T)}\cdot B_c(T) \quad (12)$$

we can conclude that the Gor'kov's equation (Eq. 8) means that:

$$\kappa(T) = \frac{\lambda(T)}{\xi(T)} = \frac{1}{1.77}\cdot\frac{\lambda(0)}{\xi(0)}\cdot\left(1.77-0.43\cdot\left(\frac{T}{T_c}\right)^2+0.07\cdot\left(\frac{T}{T_c}\right)^4\right) \quad (13)$$

By utilising another GL theory expression:

$$B_{c2}(T) = 2\cdot\left(\frac{\lambda(T)}{\xi(T)}\right)^2\cdot\frac{B_{c1}(T)}{ln(\kappa(T))+0.5} = \left(\frac{\lambda(T)}{\xi(T)}\right)^2\cdot\frac{\phi_0}{2\cdot\pi\cdot\lambda^2(T)} = (\kappa(T))^2\cdot\frac{\phi_0}{2\cdot\pi\cdot\lambda^2(T)} \quad (14)$$

and BCS expression for λ(T) for s-wave superconductor:

$$\lambda(T) = \frac{\lambda(0)}{\sqrt{1 - \frac{1}{2 \cdot k_B \cdot T} \cdot \int_0^\infty \frac{d\varepsilon}{\cosh^2\left(\frac{\sqrt{\varepsilon^2 + \Delta^2(T)}}{2 \cdot k_B \cdot T}\right)}}} \quad (15)$$

where the temperature-dependent superconducting gap $\Delta(T)$ equation can be taken from Gross *et al* [32]:

$$\Delta(T) = \Delta(0) \cdot tanh\left[\frac{\pi \cdot k_B \cdot T_c}{\Delta(0)} \cdot \sqrt{\eta \cdot \frac{\Delta C}{C} \cdot \left(\frac{T_c}{T} - 1\right)}\right] \quad (16)$$

where $\Delta C/C$ is the relative jump in electronic specific heat at T_c, and $\eta = 2/3$ for *s*-wave superconductors [32], one can obtain expression for the temperature dependent upper critical field:

$$B_{c2}(T) = \frac{\phi_0}{2 \cdot \pi \cdot \xi^2(0)} \cdot \left[\left(\frac{1.77 - 0.43 \cdot \left(\frac{T}{T_c}\right)^2 + 0.07 \cdot \left(\frac{T}{T_c}\right)^4}{1.77}\right)^2 \cdot \frac{1}{1 - \frac{1}{2 \cdot k_B \cdot T} \cdot \int_0^\infty \frac{d\varepsilon}{\cosh^2\left(\frac{\sqrt{\varepsilon^2 + \Delta^2(T)}}{2 \cdot k_B \cdot T}\right)}}\right] \quad (17)$$

Thus, four fundamental parameters of superconductor, i.e. $\xi(0)$, $\Delta(0)$, $\Delta C/C$ and T_c, can be deduced by fitting experimental $B_{c2}(T)$ data to Eq. 17. We need to clarify that $\xi(0)$ determines absolute value of $B_{c2}(0)$ amplitude, while $\Delta(0)$ and $\Delta C/C$ are deduced from the shape of $B_{c2}(T)$ curve (which is the part of Eq. 17 in square brackets).

In this paper we fit experimental $B_{c2}(T)$ data for compressed sulfur hydride to Eqs. 7, 9, and 11, 17 with the purpose to deduce/calculate fundamental superconducting parameters of this material.

III. Results and Discussions

Mozaffari et al [22] in their Fig. 1(a) defined two values for the upper critical field:

1. At the onset of superconductivity, which we will designate as $B_{c2}(T)$ (in accordance with Mozaffari et al [22] definition).
2. At zero-resistance point, which we will designate as $B_{c2,R=0}(T)$ for the clarity.

In Figs. 1-4 we show raw upper critical field data and data fits to four models:

Panel a: B-WHH model [24] (Eq. 7);

Panel b: JHC model [30] (Eq. 9);

Panel c: G model [31] (Eq. 11);

Panel d: this work model (Eq. 17).

In Figs. 1,2 we show results for Sample #1 compressed at P = 150 GPa. In Figs. 3,4 we show results for Sample #2 compressed at P = 170 GPa. In Figs. 1,3 we analysed $B_{c2,R=0}(T)$ data, and in Figs. 2,4 we analysed $B_{c2}(T)$ data. Results of all fits are presented in Table 1.

In general (Figs. 1-4, Table 1), we can conclude that all four models provide good fit quality, R, and deduced values of T_c and $\xi(0)$ for all four models are in reasonable agreement with each other. The most interesting thing we found is that fits to Eq. 17 reveal for all four $B_{c2}(T)$ datasets the value for superconducting energy gap of $\Delta(0)$ = 25-28 meV which all are in excellent agreement with the value we deduced by the analysis of critical current densities in H_3S in our previous work [19], $\Delta(0)$ = 28 meV. The latter was deduced for different H_3S sample [1] with T_c = 203 K, while in present work we analysed data for samples with lower T_c.

All deduced $B_{c2}(0)$ values (Fig. 1-4) are well below Pauli limit of:

$$B_p(0) = \frac{2 \cdot \Delta(0)}{g \cdot \mu_B} = 430 - 500\ T \gg B_{c2}(0) \quad (18)$$

where g = 2 and $\mu_B = \frac{e \cdot \hbar}{2 \cdot m_e}$ is the Bohr magneton. Following Gor'kov's note [33], Eq. 18 means that the mean-free path, l, of the electrons is large compared with the coherence length:

$$l \gg \xi(T) > \xi(0) \sim 2.5\ nm \quad (19)$$

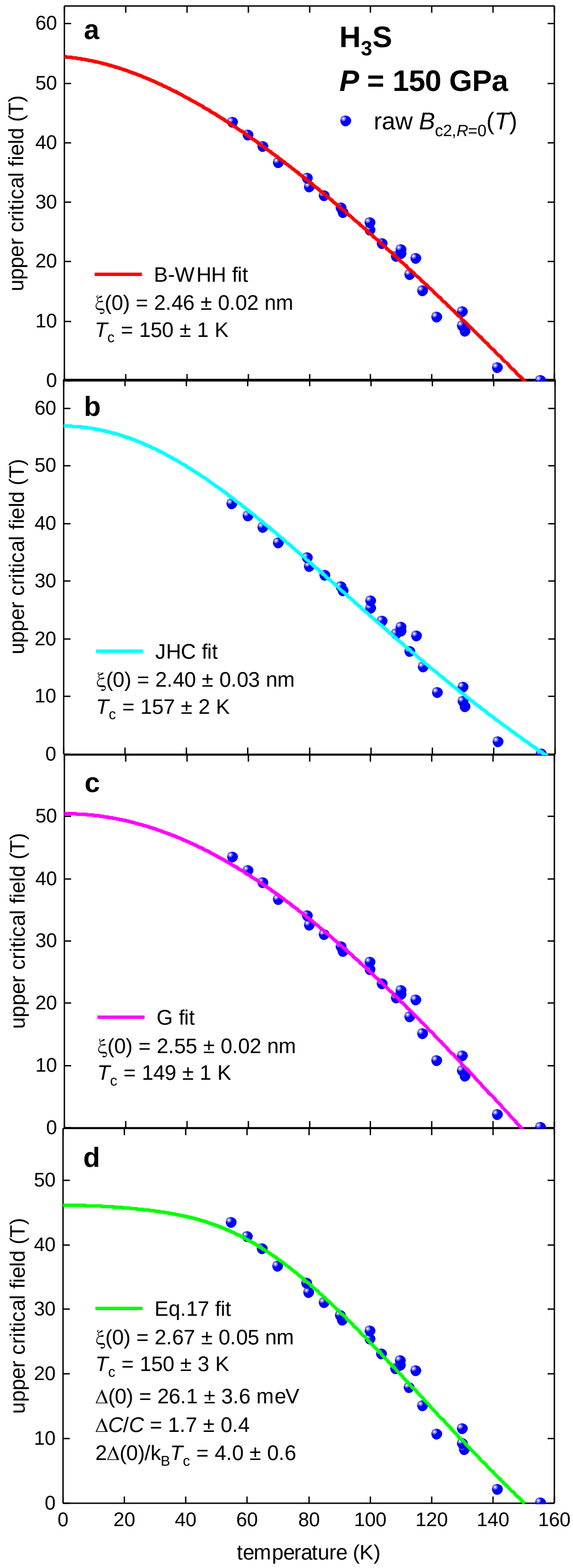

Figure 1. Superconducting upper critical field, $B_{c2,R=0}(T)$, data (blue) for compressed H_3S Sample #1 at pressure P = 150 GPa (raw data are from Ref. 22). (a) Fit to B-WHH model [24] (Eq. 7), fit quality is R = 0.9832. (b) Fit to JHC model [30] (Eq. 9), fit quality is R = 0.9785. (c) Fit to G model [31] (Eq. 11), fit quality is R = 0.9827. (d) Fit to this work model (Eq. 17), fit quality is R = 0.9832.

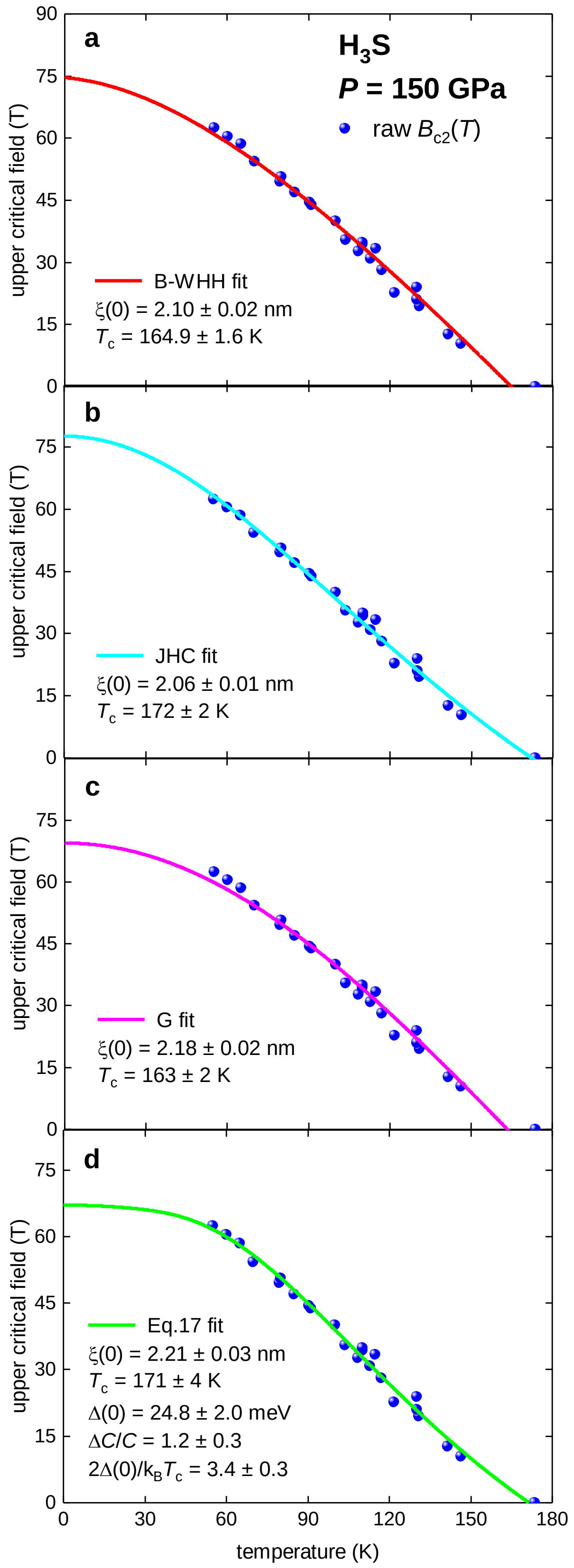

Figure 2. Superconducting upper critical field, $B_{c2}(T)$, data (blue) for compressed H_3S Sample #1 at pressure P = 150 GPa (raw data are from Ref. 22). (a) Fit to B-WHH model [24] (Eq. 7), fit quality is R = 0.9850. (b) Fit to JHC model [30] (Eq. 9), fit quality is R = 0.9908. (c) Fit to G model [31] (Eq. 11), fit quality is R = 0.9806. (d) Fit to this work model (Eq. 17); fit quality is R = 0.9914.

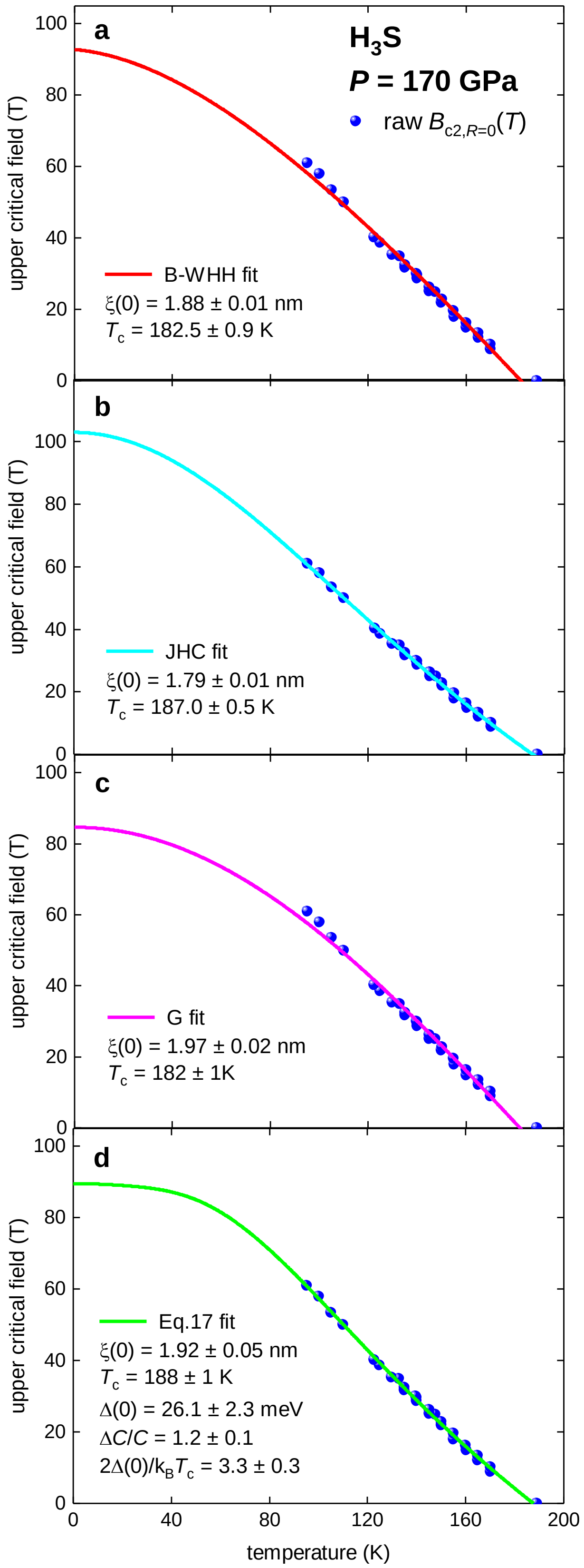

Figure 3. Superconducting upper critical field, $B_{c2,R=0}(T)$, data (blue) for compressed H_3S Sample #2 at pressure P = 170 GPa (raw data are from Ref. 22). (a) Fit to B-WHH model [24] (Eq. 7), fit quality is R = 0.9901. (b) Fit to JHC model [30] (Eq. 9), fit quality is R = 0.9978. (c) Fit to G model [31] (Eq. 11), fit quality is R = 0.9879. (d) Fit to this work model (Eq. 17); fit quality is R = 0.9979.

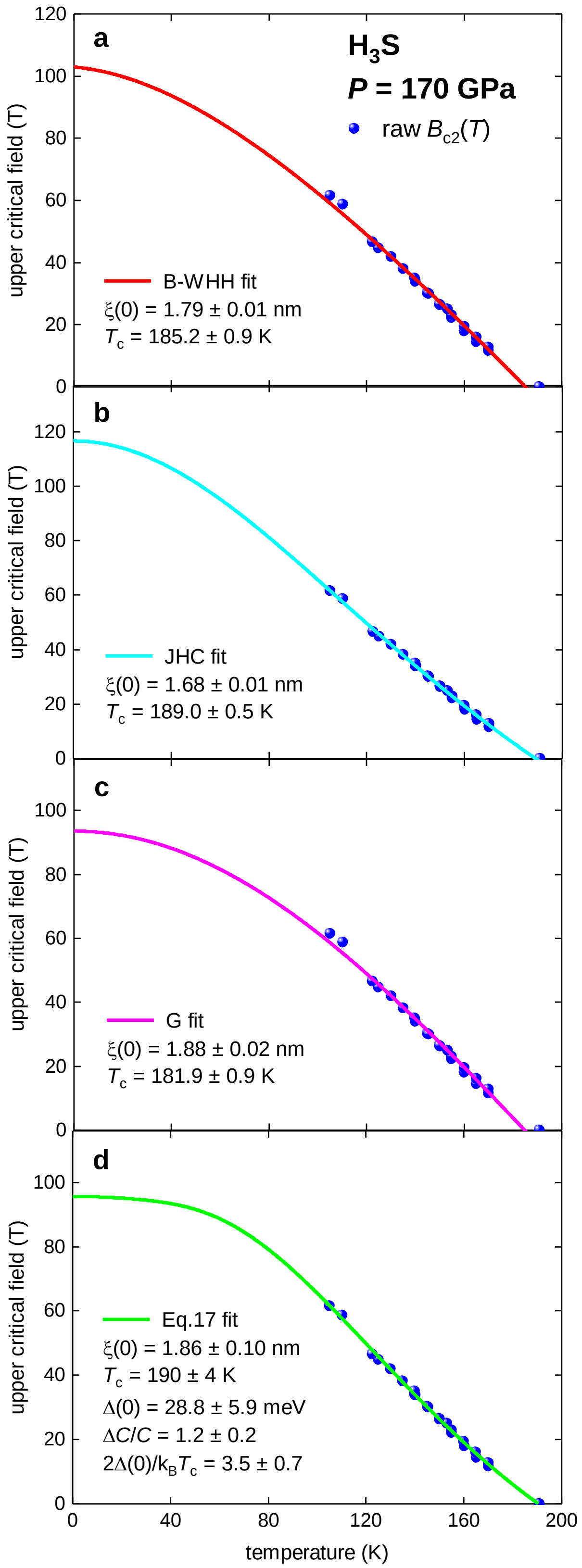

Figure 4. Superconducting upper critical field, $B_{c2}(T)$, data (blue) for compressed H_3S Sample #2 at pressure P = 170 GPa (raw data are from Ref. 22). (a) Fit to B-WHH model [24] (Eq. 7), fit quality is R = 0.990. (b) Fit to JHC model [30] (Eq. 9), fit quality is R = 0.9978. (c) Fit to G model [31] (Eq. 11), fit quality is R = 0.9886. (d) Fit to this work model (Eq. 17); fit quality is R = 0.9981.

This is interesting result, if we take in account that H_3S is formed by chemical reaction which occurs within the diamond anvil volume:

$$3H_2S \rightarrow 2H_3S + S \quad (20)$$

and pure sulfur is always presented as post-reacted product in the studied sample.

However, Eq. 18 tells us that two phases, i.e. H_3S and S, are reasonably well separated from each other and there is a very low level of atomic disordering within superconducting H_3S phase, which has lattice parameter of a = 0.3092 nm [34].

The next step of the analysis is the comparison of v_F, ε_F, T_F values calculated directly by Eq. 3 (because fits to Eq. 17 provide both required quantities, i.e. $\xi(0)$ and $\Delta(0)$) with v_F values calculated by Eq. 4 in assumption of two extreme coupling strength scenario of α = 3.53 and α = 4.70. Overall, deduced/calculated v_F for H_3S are in the range of v_F = (2.0-3.8) x10^5 m/s which equals to v_F of nickel and cobalt at normal conditions [35] and is approximately equal to the universal nodal Fermi velocity of the superconducting cuprates [36].

Table 1. Deduced parameters for H_3S superconductor. We assumed that electron effective mass in H_3S is m_{eff} = 2.76 m_e [10].

Pressure (GPa)	Raw data	Model	Deduced T_c (K)	Deduced $\xi(0)$ (nm)	Assumed/deduced $\frac{2\cdot\Delta(0)}{k_B\cdot T_c}$	$\Delta C/C$	v_F (10^5 m/s)	$\Delta(0)$ meV	ε_F eV	$\Delta(0)/\varepsilon_F$	T_F (10^3 K)	T_c/T_F
150	$B_{c2,R=0}$ (T)	B-WHH	150 ± 1	2.46 ± 0.02	3.53		2.68 ± 0.03	22.8 ± 0.2	0.56 ± 0.01	0.040 ± 0.001	6.5 ± 0.2	0.023 ± 0.001
					4.70		3.57 ± 0.04	30.4 ± 0.04	1.00 ± 0.02	0.030 ± 0.001	11.6 ± 0.4	0.013 ± 0.001
		JHC	157 ± 2	2.40 ± 0.03	3.53		2.74 ± 0.03	23.9 ± 0.4	0.59 ± 0.03	0.041 ± 0.002	6.8 ± 0.2	0.023 ± 0.001
					4.70		3.65 ± 0.05	31.8 ± 0.4	1.04 ± 0.02	0.030 ± 0.002	12.1 ± 0.5	0.013 ± 0.001
		G	149 ± 1	2.55 ± 0.02	3.53		2.76 ± 0.03	22.7 ± 0.2	0.60 ± 0.01	0.038 ± 0.002	6.9 ± 0.2	0.021 ± 0.001
					4.70		3.68 ± 0.04	30.2 ± 0.3	1.06 ± 0.02	0.028 ± 0.001	12.3 ± 0.5	0.012 ± 0.001
		Eq. 16	150 ± 3	2.67 ± 0.05	4.0 ± 0.6	1.7 ± 0.4	3.33 ± 0.45	26.1 ± 3.6	0.87 ± 0.12	0.030 ± 0.004	10.1 ± 1.4	0.015 ± 0.002
					3.53		2.51 ± 0.03	25.1 ± 0.3	0.50 ± 0.01	0.051 ± 0.002	5.8 ± 0.2	0.029 ± 0.001

		B-WHH	165 ± 2	2.10 ± 0.02	4.70		3.35 ± 0.03	33.4 ± 0.3	0.88 ± 0.02	0.038 ± 0.002	10.2 ± 0.2	0.016 ± 0.001
		JHC	172 ± 2	2.06 ± 0.01	3.53		2.57 ± 0.03	26.2 ± 0.3	0.52 ± 0.01	0.050 ± 0.002	6.0 ± 0.2	0.029 ± 0.001
					4.70		3.42 ± 0.03	34.8 ± 0.3	0.92 ± 0.02	0.038 ± 0.001	10.7 ± 0.2	0.016 ± 0.001
	$B_{c2}(T)$	G	163 ± 2	2.18 ± 0.02	3.53		2.58 ± 0.05	24.8 ± 0.3	0.52 ± 0.02	0.048 ± 0.002	6.0 ± 0.2	0.027 ± 0.001
					4.70		3.43 ± 0.07	33.0 ± 0.3	0.92 ± 0.05	0.036 ± 0.002	10.7 ± 0.2	0.015 ± 0.001
		Eq. 16	171 ± 4	2.21 ± 0.03	3.4 ± 0.3	1.2 ± 0.3	2.6 ± 0.3	24.8 ± 2.0	0.54 ± 0.06	0.046 ± 0.005	6.3 ± 0.5	0.027 ± 0.003
170	$B_{c2,R=0}(T)$	B-WHH	182.5 ± 0.9	1.88 ± 0.01	3.53		2.50 ± 0.03	27.8 ± 0.1	0.49 ± 0.01	0.057 ± 0.002	5.7 ± 0.2	0.032 ± 0.002
					4.70		3.32 ± 0.02	37.0 ± 0.2	0.87 ± 0.01	0.043 ± 0.001	10.0 ± 0.2	0.018 ± 0.001
		JHC	187.0 ± 0.5	1.79 ± 0.01	3.53		2.43 ± 0.01	28.4 ± 0.1	0.46 ± 0.01	0.062 ± 0.001	5.4 ± 0.1	0.035 ± 0.001
					4.70		3.23 ± 0.01	37.9 ± 0.1	0.82 ± 0.01	0.046 ± 0.001	9.5 ± 0.1	0.020 ± 0.001
		G	182 ± 1	1.97 ± 0.02	3.53		2.61 ± 0.01	27.7 ± 0.1	0.53 ± 0.01	0.052 ± 0.001	6.2 ± 0.1	0.030 ± 0.001
					4.70		3.47 ± 0.01	36.9 ± 0.1	0.94 ± 0.01	0.052 ± 0.001	11.0 ± 0.2	0.017 ± 0.001
		Eq. 16	188 ± 1	1.92 ± 0.05	3.3 ± 0.3	1.2 ± 0.1	2.4 ± 0.2	26.1 ± 2.3	0.44 ± 0.05	0.059 ± 0.006	5.0 ± 0.5	0.037 ± 0.004
	$B_{c2}(T)$	B-WHH	185.2 ± 0.9	1.79 ± 0.01	3.53		2.40 ± 0.01	28.2 ± 0.1	0.45 ± 0.01	0.062 ± 0.001	5.3 ± 0.1	0.035 ± 0.001
					4.70		3.20 ± 0.01	37.5 ± 0.1	0.80 ± 0.02	0.047 ± 0.002	9.3 ± 0.2	0.020 ± 0.001
		JHC	189.0 ± 0.5	1.68 ± 0.01	3.53		2.30 ± 0.01	28.7 ± 0.1	0.42 ± 0.01	0.069 ± 0.002	4.8 ± 0.2	0.039 ± 0.001
					4.70		2.07 ± 0.01	38.3 ± 0.1	0.74 ± 0.02	0.052 ± 0.002	8.6 ± 0.2	0.022 ± 0.001
		G	181.9 ± 0.9	1.97 ± 0.02	3.53		2.48 ± 0.02	27.7 ± 0.1	0.48 ± 0.01	0.057 ± 0.002	5.6 ± 0.3	0.033 ± 0.002
					4.70		3.30 ± 0.02	36.8 ± 0.1	0.85 ± 0.02	0.043 ± 0.002	9.9 ± 0.3	0.018 ± 0.001
		Eq. 16	190 ± 4	1.86 ± 0.10	3.5 ± 0.7	1.2 ± 0.2	2.6 ± 0.4	28.8 ± 5.9	0.51 ± 0.09	0.056 ± 0.009	6.0 ± 1.0	0.032 ± 0.006

Examination of the values in Table I leaded us to three important findings:

1. The ratio of the superconducting energy gap, $\Delta(0)$, to the Fermi energy, ε_F, in all considered scenarios (including direct deduction by Eq. 17) is within interval of $0.03 < \Delta(0)/\varepsilon_F < 0.07$. These values characterize H_3S material as an unconventional superconductor, by illustration, conventional niobium, Nb, has the ratio which is at least two orders of magnitude lower, i.e. $\Delta(0)/\varepsilon_F = 3\cdot10^{-4}$ [37].

2. The most straightforward way to see our conclusion that H_3S is unconventional superconductor is to add T_c and T_F data for H_3S on the plot of T_c versus T_F where other

superconductors are shown. In this plot (Fig. 5) (data in Fig. 5 were adopted from Uemura [38], Ye et al [39], Qian et al [40], and Hashimoto et al [41]) all unconventional superconductors are located within a narrow band of $0.01 < T_c/T_F < 0.05$. We note that Uemura [38] stated that there is the upper limit for $T_c/T_F = 0.05$ for all known superconductors. In all considered scenarios, H_3S has ratios within interval of $0.012 < T_c/T_F < 0.039$ (Fig. 5 and Table 1). It is clearly visible in Fig. 5 that H_3S is in the same band where all unconventional superconductors, particularly heavy fermions and cuprates, are. In this regard, H_3S is located just above Bi-2223 phase. In this regard, H_3S is the material which is located at the position where majority of others unconventional superconductors placed.

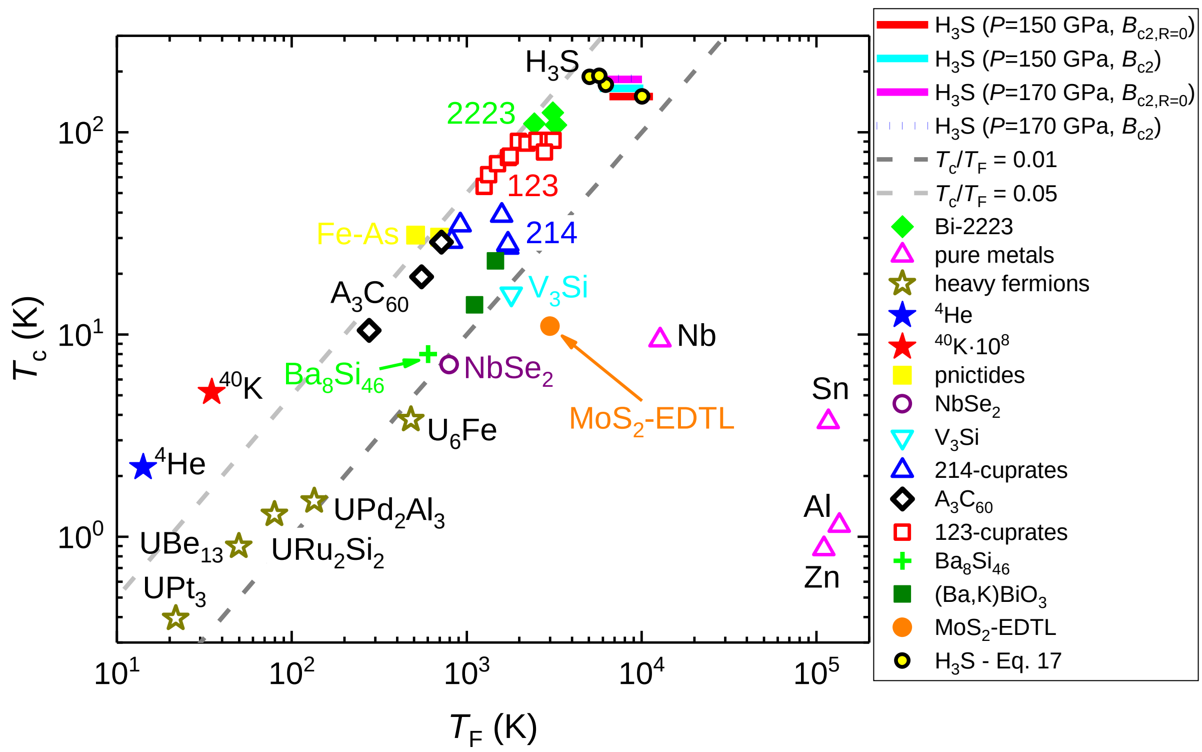

Figure 5. A plot of T_c versus T_F obtained for most representative superconducting families. Data was taken from Uemura [38], Ye et al [39], Qian et al [40], and Hashimoto et al [41].

3. We also can see that despite of very different assumptions and varieties of the upper critical field data definition, the Fermi velocity is within reasonably narrow interval of $v_F = (2.1\text{-}3.7)\cdot 10^5$ m/s. This value is about two times lower than v_F of alkali metals at normal

conditions [35,37] and it approximately equals to the universal nodal Fermi velocity of the superconducting cuprates [36]. This is another manifestation that H_3S should be classified as unconventional superconductor.

Even though the original paper from Drozdov et. al. [1] stated that H_3S is conventional superconductor, and this point of view was very quickly widely accepted by the scientific community [3], we must note that at that time there were no available experimental data which supported this point of view. One of prerequisites of phonon mediated mechanism in H_3S is the strong-coupling electron-phonon interaction (references on original papers can be found in Ref. 13), which we cannot confirm neither by the analysis of experimental critical current densities [20], nor by the analysis of experimental upper critical field data presented herein. Instead our analysis gives clear evidence that H_3S is weak-coupled superconductor, with the ratio:

$$3.3 \pm 0.3 < \frac{2 \cdot \Delta(0)}{k_B \cdot T_c} < 4.0 \pm 0.6 \qquad (21)$$

and average value of

$$\frac{2 \cdot \Delta(0)}{k_B \cdot T_c} = 3.55 \pm 0.31 \qquad (22)$$

which is remarkably closed to weak-coupling limit of BCS theory of 3.53. Average absolute value of the ground state superconducting energy gap is:

$$\Delta(0) = 26.5 \pm 1.7\ meV \qquad (23)$$

This value is in a very good agreement with $\Delta(0)$ = 27.8 meV which we deduced in our previous paper by the analysis of critical current density in H_3S [19] for sample with T_c = 203 K.

IV. Conclusion

In this paper, we analysed the upper critical field data for compressed H_3S which were recently released by Los-Alamos Laboratory [22]. Result of our analysis showed that compressed H_3S should be classified as another member of unconventional superconductor family.

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