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How to soothe the turmoil in the field of pressure-induced superconductivity in the hydrides

Liling Sun, Qi Wu, Tao Xiang & Ho-kwang Mao

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A crucial issue in condensed-matter physics is the assessment of superconducting diamagnetism in highly compressed hydrides. We propose a suitable reference sample that can be used to gain more consensus.

In a recently published article in *Nature*[1], journalist Dan Garisto described the "turmoil" in the research field of pressure-induced high-temperature superconductivity in hydrides: not merely the usual disputation among researchers but a fundamental debate on how science should be conducted. The critical issue is the reliability of the validation of the expulsion of internal magnetic field – the superconducting diamagnetism – when small-size hydrides under ultrahigh pressure (over 100 GPa) become superconducting[2–6]. In an effort to resolve this problem, we propose a method in which a reference sample can be adopted to assess the dependability of the ultrahigh-pressure susceptibility measurement systems, to identify the results of pressure-induced superconducting diamagnetism in the samples being investigated and to estimate the relative superconducting volume between the sample being investigated and the reference sample across various research groups.

We suggest that a good reference sample would be the ambient-pressure superconducting $Nb_{0.44}Ti_{0.56}$ alloy, because it can retain its bulk superconducting property under pressure up to 261 GPa (ref. 7). Suitable comparisons between the properties of this alloy and the hydrides under high pressure should provide the community with a resolution. The use of the reference may even guide the community towards a consensus on an appropriate way of evaluating the experimental results in the studies of pressure-induced high-temperature superconductivity in hydrides and other materials.

The reason for the turmoil: challenges in capturing the diamagnetic signal

The characteristic feature of materials exhibiting superconductivity is their ability to conduct electricity without resistance and to expel magnetic fields, displaying complete diamagnetism below a critical temperature. This decrease in resistance, or the appearance of a state with seemingly zero resistance, has been widely observed in many hydrides under ultrahigh pressures[8], but unfortunately, conclusive evidence of the diamagnetic property has not yet been shown. This is primarily due to the technical challenges associated with capturing the weak superconducting diamagnetic signal from a small sample compressed in a diamond anvil cell. The typical size of the metallic hydride samples loaded in the cell is about 20–40 μm in a nearly square shape and 1–2 μm in thickness. This small size is crucial for applying high pressure to the sample. However, this size limitation inevitably results in a weaker diamagnetic signal from the superconducting phase. In particular, almost all the metallic hydride samples are prepared using laser heating under ultrahigh-pressure conditions. In the process, a thin metallic plate is usually surrounded by hydrogen gas or the ammonia borane that serves as a hydrogen source[8]. This procedure makes it challenging to achieve a uniform sample because uneven heating and cooling, along with consequent chemical gradients within the sample, tend to lead to the presence of mixed phases in the sample.

The inhomogeneity of the hydrides prepared by the current method is often reflected in the resistance–temperature plots, which show noticeable steps[2,8]. The existence of inhomogeneous phases further weakens the superconducting diamagnetic signal. To address these challenges and alleviate the turmoil in the field of ultrahigh pressure-induced superconductivity in hydrides, here we propose a solution.

The suggested solution: comparison to a suitable reference sample

A standard sample should be selected to serve as a reference. This sample should at least possess all the following characteristics:

(1) It must have an ambient-pressure bulk superconducting nature with a 100% superconducting volume fraction, and robust bulk superconductivity in a wide pressure range, preferably extending to 200 GPa and beyond. This pressure range should encompass most of the range investigated in high-pressure studies on superconductivity in hydrides, thus enabling the reference sample to be used to validate the measurement system and experimental results among different research groups.
(2) Its critical temperature (T_c) must be high enough to allow measurements in commercial cryostat systems.
(3) It must exhibit no pressure-induced structural phase transition over an extensive pressure range, thus providing continuous superconducting diamagnetism.
(4) It must be commercially accessible so that researchers can obtain the same reference material.

We find that the commercially available superconducting $Nb_{0.44}Ti_{0.56}$ alloy is an excellent candidate that meets all the specified criteria. Previous studies have demonstrated that this alloy is a well established superconductor, with T_c about 9.6 K at ambient pressure. It also exhibits unique superconducting characteristics – its robust superconductivity against volume shrinkage can persist from 1 bar to 261 GPa (ref. 7), confirmed by its zero resistance in this pressure range.

Functions of the reference sample: evaluation of the measurement system and results of superconducting diamagnetism from highly compressed hydrides

The primary uses of the reference sample are:

(1) To assess the reliability of the susceptibility measurement system. For any system to be deemed reliable in this context, it should unambiguously capture the bulk superconducting diamagnetism exhibited in the $Nb_{0.44}Ti_{0.56}$ alloy. If it fails to detect the peak-like superconducting diamagnetic signatures from $Nb_{0.44}Ti_{0.56}$ in the pressure range investigated, as shown in ref. 9, the system being tested cannot provide dependable evidence to substantiate the presence of pressure-induced superconductivity in other samples.

(2) To provide unambiguous diamagnetic data through comparison with the investigated samples. After obtaining diamagnetic data from modulated alternating-current susceptibility measurements of the $Nb_{0.44}Ti_{0.56}$ sample[9], the measurements from the samples being investigated can be juxtaposed for analysis. This comparative approach will ensure the reliability of the results from different research groups.

(3) To estimate the relative superconducting volume fraction. In instances where the sample exhibits non-bulk superconducting behaviour (such as in the inhomogeneous hydrides), the superconducting volume fraction can be estimated by comparing the superconducting diamagnetic signals per unit volume between the reference sample and the investigated sample. This method offers a way to scrutinize the non-bulk superconducting nature, such as filamentary superconductivity.

More generally, this reference material is also essential for investigating the diamagnetic properties of other candidate pressure-induced superconductors. Thus, with the improvement of experimental methods and techniques, we optimistically anticipate that more and more reliable, controllable and comparable results will be obtained and thus a better consensus on understanding the high-T_c superconductivity of the highly compressed hydrides will be achieved.

Liling Sun[1,2] ✉, **Qi Wu**[2], **Tao Xiang**[2] **& Ho-kwang Mao**[1,3]

[1]Center for High Pressure Science and Technology Advanced Research, Beijing, China. [2]Institute of Physics, Chinese Academy of Sciences, Beijing, China. [3]Shanghai Key Laboratory of MFree, Shanghai Advanced Research in Physical Sciences, Shanghai, China.

✉e-mail: lilingsun@hpstar.ac.cn

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Competing interests

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