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Hydride superconductivity is here to stay

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Do hydrides support genuine superconductivity or not? We examine some key papers, and conclude that they do

One of the forefront fields of modern superconductivity research is that on hydrides at high pressures. Over the past few years, this research has attracted considerable publicity, of which a substantial fraction has been negative. Scientific fraud has been committed and exposed, and arguments continue about specific aspects of data presented in some other papers. Among all the noise that is being generated, one might lose sight of the big-picture question of whether the field is on solid foundations or not, that is, whether high-pressure hydrides host superconductivity at all. Here, we readdress this central issue. We select and critically examine what we identify as six key papers on the topic. We have all spent substantial portions of our careers working on superconductivity, so hope that the conclusions that we reach will carry at least some weight. We also decided to include among our authorship team only people who have never worked directly on hydride superconductivity, so that our examination of the scientific facts can be as impartial as possible. We conclude that it is overwhelmingly probable that the phenomenon of hydride superconductivity is genuine.

Challenges of sample preparation and measurement

What most people would regard as the breakthrough paper in hydride superconductivity was published in 2015 by the group at the Max Planck Institute in Mainz[1]. It described the extreme compression of H_2S to pressures over one million times higher than that of our atmosphere, and the observation of a transition reported to be superconductivity at approximately 200 K, attributed to the formation of H_3S. This famous work was followed by experiments in which mixtures of hydrogen and metal atoms were both compressed and heated, creating in situ chemical reactions to form compounds directly in the pressure cells, which were subsequently cooled to check for signs of superconductivity.

For our purpose of assessing experimental information, we restrict ourselves to two classic probes of superconductivity, resistance and magnetization, as superconducting responses to such probes are so well known. This choice should not, however, be taken to imply any judgement on the work that is also going on to develop new measurement techniques specifically suited to the hydride sample environment[2].

The challenges of performing experiments on hydrides should not be underestimated. Most of the groups involved have been very open about the nature of the high-pressure matter that is produced in such experiments. It is chemically inhomogeneous, and the phases that exist in the sample are often hard to identify with certainty. This is not surprising: it is an environment in which it is very difficult to use the standard techniques of solid-state chemistry.

For the purposes of analysing data from physical measurements, the at-present unavoidable inhomogeneity must be borne in mind. One inevitably expects variations in details of electrical resistance data, for example. If there is superconductivity in such an environment, some transitions will be the result of establishing fragile percolation paths, whereas others will be incomplete because only a non-connected fraction of the sample is superconducting. In the case of magnetic measurements, the sample environment gives a further series of challenges. Even using the smallest cells specially built for the purpose, the mass of the cell is approximately 100 million times larger than that of the potential superconductor inside, so extreme care must be taken to reduce background signals to the level where any superconducting contribution can be observed in the data.

Resistance, upper critical field and magnetization

We begin with an examination of the key resistive evidence for superconductivity. Many measurements have been carried out using four-terminal measurements in which, for a homogeneous superconductor, the resistance would fall to the noise floor of the measurement apparatus in the superconducting state. In some cases, for example in refs. 1–3, this drop in resistance is seen, likely because a percolation path has been established through the pressurized material rather than because a homogenous sample has been realized. In others, for example refs. 4,5, zero resistance is not achieved, but there is evidence from real-space imaging for why a complete percolation path is unlikely.

In isolation, this kind of resistive evidence would not be sufficient for an assertion of superconductivity. However, it is supplemented in the literature by numerous reports of the suppression of the resistive transition by an applied magnetic field. We reproduce two examples, from refs. 4 and [5], in Fig. 1.

Several further aspects of the data shown in Fig. 1 merit comment. Firstly, the data in Fig. 1a were taken at the US National High Magnetic Field Laboratory in Tallahassee and Los Alamos, by a team led by scientists otherwise unconnected with the Mainz group in which the pressurized sample was prepared. Secondly, the sample studied in the work shown in Fig. 1b was prepared by an entirely different group at the University of Bristol, using an entirely different synthesis route. The critical temperatures reported for H_3S in the Mainz experiment[1], the Los Alamos experiment[4] and the Bristol experiment[5] agree within experimental error, as do the deduced upper critical fields of the Tallahassee/Los Alamos and Bristol studies (see Fig. 1c). This level of reproducibility of findings between different groups is one of the requirements for claims of any new phenomenon to be regarded as credible. In this context we further note that the sample preparation and measurement routes used in refs. 1–3 were also independent.

Next, we turn our attention to SQUID measurements of magnetization. These are extremely challenging, and have only been reported by the Mainz group. The cell components, and minute levels of impurities within or on their surface, can give background signals (diamagnetic or paramagnetic, depending on details of the impurities and cell components). In the original 2015 paper[1], magnetization loops were shown without the so-called virgin curve, which is the data seen on the first cycle of the loop following zero-field cooling, and gives the most direct information about the magnetic response being diamagnetic, a crucial property of a superconductor. Since then, data have been reported including virgin curves[6].

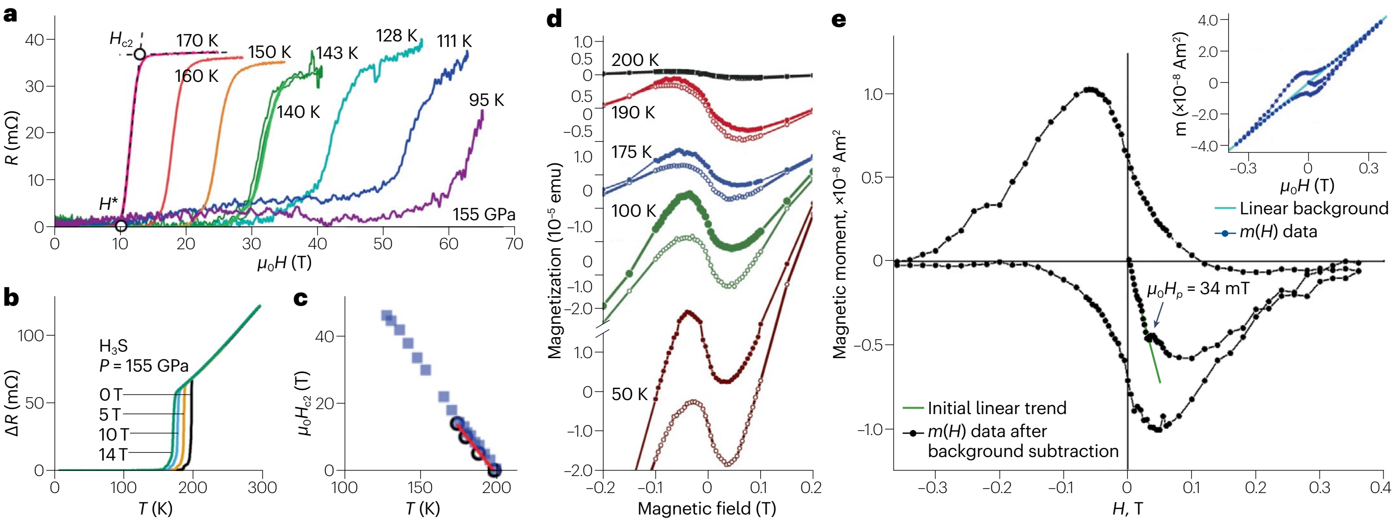

Fig. 1 | Key measurements of multiple samples of H_3S at different pressures. In both **a** and **b**, the samples are pressurized to 155 GPa, at which transitions at approximately 200 K are seen. **a**, The magnetic field dependence of the resistance is shown at a series of fixed temperatures studied to high fields in a DC magnet ($T > 145$ K) and pulsed-field magnet ($T < 145$ K). The higher noise levels in the pulsed field work are not unusual; reproduced from ref. 4. **b**, Resistive transitions as a function of temperature for a series of fixed fields of 14 T and below, performed on a completely different sample from that in **a** (ref. 5). A contribution attributed to sulfur surrounding the H_3S has been subtracted, so the data are shown as Δ*R* rather than as *R*. **c**, Upper critical fields extracted from the two different experiments (shown in blue[4] and open black circles[5]) are in excellent agreement. **b** and **c** reproduced from ref. 5. **d**,**e**, Magnetization loops for two samples at applied pressure of 155 GPa (reproduced from ref. 1) and 140 GPa (reproduced from ref. 6). The virgin curve – the initial linear trend marked by the green line – included in **e**. The main feature of the loops is visible without any subtraction (inset to **e**). In **d** the loop is also seen to close at $T_c \sim 200$ K (black data), in line with expectations for a superconductor.

Figure 1d shows the data from ref. 1. The hysteretic part of the signal disappears (the hysteresis loops close) at T_c, fully consistent with their origin being superconductivity. Figure 1e shows the loop reported in ref. 6. Data including the background are shown in the inset. Even before background subtraction, the data for the virgin curve go negative, in low applied fields, offering strong evidence that diamagnetism is observed in the raw data. The simple subtraction of the linear background gives the curve shown in the main plot, which has the main qualitative features expected of a superconducting hysteresis loop in the presence of flux trapping.

Conclusion

The goal of this Comment has neither been to review the whole field of hydride superconductivity nor to discuss the issues of detail about H_3S work raised in recent correspondence on arXiv and other preprint servers and in the popular press. It has been to assess the broader scientific question of whether hydride superconductivity is genuine or not. Based on the data we have shown and discussed here, in our professional judgement it is overwhelmingly probable that it is. It is also exciting and ground-breaking, making it even more important that data be made publicly available and subjected to reasonable scientific scepticism. The most useful form for such scepticism to take is experiments attempting to confirm or deny those already performed, combined with others building on the existing knowledge and driving it forward by introducing new compounds and measurement techniques. Our message to funding agencies is to continue to support good proposals to drive hydride superconductivity forward, and our message to young scientists is to enter the field with curiosity and enthusiasm if it is the kind of science that intrigues you. Finally, our message to the field's pioneers is to congratulate and thank you for your important work.

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Competing interests

The authors declare no competing interests.