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LETTERS TO THE EDITORS

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What led to retraction of the article on room-temperature superconductivity in the journal *Nature*: a series of oversights or falsification?

A V Sadakov, O A Sobolevskiy, V M Pudalov

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Abstract. In 2020, the journal *Nature* published an article under the notorious title “Room-temperature superconductivity in a carbonaceous sulfur hydride” (*Nature* 586 373–377 (2020)) that caused, without exaggeration, an effect like an exploding bomb; after all, it was stated that one of the most important problems in modern physics (implementation of superconductivity at room temperature) has already been solved! In two years, the article has been cited over 500 times and read over 100,000 times. However, in the scientific community, the article led to a great deal of questions, skepticism, and severe criticism. Eventually, on September 26, 2022, *Nature* retracted this publication. We give here the main reasons for the retraction and our commentary on the significance of this act for the physics of high-temperature superconductivity in general and the superconductivity of hydrides in particular.

Keywords: room-temperature superconductivity, high pressures, hydrides

1. Introduction

Questions and problems regarding high-temperature superconductivity (HTSC) were repeatedly covered in the journal *Physics–Uspekhi* (*Usp. Fiz. Nauk*) by the 2003 Nobel Prize winner in physics Vitaly Lazarevich Ginzburg (see [1–4]), while the problem of achieving superconductivity at room temperature (so-called room-temperature superconductivity — RTSC) was listed by V L Ginzburg among the most important problems facing physics in the 21st century, along with the implementation of a controlled fusion reaction (see [2–4]).

It is precisely in view of the obvious importance of solving the problem of RTSC that the appearance in 2020 in the journal *Nature* of an article [5], titled “Room temperature superconductivity in a carbonaceous sulfur hydride,” aroused great interest in the scientific (and not only in the scientific) community: after all, it was stated that one of the most important problems in modern physics (achieving superconductivity at room temperature) is already solved! It is clear that the article immediately attracted the attention of all scientists around the world, working in the field of HTSC and RTSC: in two years, the article [5] was cited more than 500 times and read more than 100 thousand times. But, in the scientific community, the article led to many questions, skepticism, and harsh criticism. In the end, on September 26, 2022, *Nature* was forced to retract the above publication [6].

In view of the great importance of solving the problem of RTSC, in the last few years, special attention of the scientific community has been riveted to superconductivity in hydrides at ultrahigh pressure. It was expected that namely among these hydrides, with their record critical temperatures [7–11], a substance becoming a superconductor at room temperature would be discovered.

It should be noted that eight years have passed since the publication of the pioneering work [7] on superconductivity in sulfur hydride,[1] and now we can state the appearance in physics of a whole new direction devoted to the study of superconductivity in superhydrides. The record values of the critical temperature reported one after another are certainly important, but, in our opinion, the already accumulated various evidence of the electron-phonon mechanism of electron pairing in superhydrides is even more important — a mechanism whose capabilities were previously underestimated by many (see the Nobel lecture by V L Ginzburg [3]). In the field of superhydrides, more than a thousand scientific papers have already been published, most of them representing numerical theoretical calculations. There are two simple

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A V Sadakov[(a)], **O A Sobolevskiy, V M Pudalov**[(b)]
Lebedev Physical Institute, Russian Academy of Sciences,
Leninskii prosp. 53, 119991 Moscow, Russian Federation
E-mail: [(a)]sadakovav@lebedev.ru, [(b)]pudalov@lebedev.ru

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[1] See also review [8] in the special issue of *Physics–Uspekhi* (*Usp. Fiz. Nauk*) devoted to the 100th anniversary of the birth of V L Ginzburg.

explanations for the dominance of theoretical publications. First, computing power and evolutionary algorithms have made great progress in predicting new stable structures, and second, experimental studies of hydrides are associated with ultrahigh pressures and concomitant objective difficulties.

The dominance of the number of theoretical studies over experimental ones led to the fact that almost all new superconducting hydrides were first theoretically predicted and then experimentally discovered. Over the subsequent 7 years, dozens of new superhydrides were predicted and experimentally discovered, including ThH_{10} with $T_c = 161$ K [9], YH_6 with $T_c = 224$ K [10], and LaH_{10} with $T_c = 250$ K [11]; most of the new results were further supported by measurements of their various superconducting properties and verified in measurements by independent groups. In 2020, one high-profile exception appeared: an article [5] was published, where it was stated that a certain combination of hydrogen, sulfur, and carbon, so-called. 'carbonaceous sulfur hydride,' becomes superconducting at a temperature of 287 K (i.e., $+14\,^{\circ}$C!). As proof of superconductivity, the article in *Nature* cited data on the drop in resistance and a diamagnetic jump in magnetic susceptibility. However, in the article mentioned, neither the results of X-ray diffraction analysis nor the numerical calculation of the stability of the C–S–H system were presented. Soon after, many critical articles appeared [12–16] which cast doubt on the published experimental data of this group, their interpretation, and, most importantly, the very assertion of superconductivity in 'sulfur carbon hydride.' Finally, on September 26, 2022 the journal *Nature* retracted the article by Snyder et al. [5], with rather mild wording: "We have now established that some key data processing steps — namely, the background subtractions applied to the raw data used to generate the magnetic susceptibility plots in Fig. 2a and Extended Data Fig. 7d — used a nonstandard, user-defined procedure. The details of the procedure were not specified in the paper and the validity of the background subtraction has subsequently been called into question" (see [6] https://www.nature.com/articles/s41586-022-05294-9).

We present below a brief review of the criticism of the results published by Snyder et al. [5], which, together with the withdrawal of the publication itself [6], practically states that there is no room temperature superconductivity in the C–S–H compound, and, accordingly, the achievement of this goal apparently remains a matter for the future.

2. Search for carbonaceous sulfur hydride. Theory and experiment

Almost immediately after the publication of Snyder's work, a great deal of effort was invested in numerical searches for thermodynamically stable structures in the C–S–H system. Since neither elemental nor X-ray diffraction analysis of this system was carried out in [5], many probable structural types had to be checked. In [17–19], hundreds of variants of compounds of the C–S–H system were studied. The main conclusion of these studies is that diagrams of the thermodynamic stability of the carbon–sulfur–hydrogen system do not even have a weakly expressed region with a minimum of energy, which is required for the formation of a stable phase. Only a few potential compounds have a relatively low energy, but they can only be metastable and, when heated, must decompose into sulfur hydride. The only reasonable stability zone is the zone of H_3S lightly doped with carbon [20]. However, in this case, the low carbon content, first, contradicts the 1:1 ratio of the mixture of carbon and sulfur stated in the Snyder's work, and, second, it can hardly lead to a cardinal increase in T_c in the H_3S system (maximum $T_c = 203$ K in the H_3S system was found at a pressure of 155 GPa, and, with a further pressure elevation, T_c decreases).

With regard to experimental confirmation, at the moment, no independent experimental group has been able to synthesize the claimed compound C–S–H. Thus, neither the authors themselves nor other experimental and theoretical groups were able to answer the questions: what kind of substance 'superconducted' in Snyder's work, and did it 'superconduct' in general? The lack of detailed data, as well as the lack of independent experimental and theoretical confirmation, is especially puzzling in view of the fact that all other superconducting hydrides with record high T_c (such as H_3S, LaH_{10}, YH_6) have been studied by independent groups and their structure is well known from calculations and X-ray diffraction analysis.

3. Criticism of experimental data on the transition to the superconducting state in terms of resistance and magnetic susceptibility

The experimental work of Snyder [5] contains a number of obvious errors and inconsistencies. Consider first the problems associated with transport studies. The authors report measurements of superconducting transitions in magnetic fields up to 9 T. The transitions, surprisingly narrow in temperature, are immediately striking, which, first, should not be inherent in knowingly inhomogeneous compounds of complex composition. Second, these 'superconducting' transitions do not broaden at all in a magnetic field. This behavior is not only uncharacteristic of high-temperature superconductors, it has never been seen in any compound among hydrides, cuprates, iron-containing superconductors, or magnesium diboride. The authors themselves claim that their superconductor belongs to the so-called weak type II superconductors, in which, indeed, superconducting transitions are narrow and barely broaden in a magnetic field. But, as was shown in [12], the conclusion that the C–S–H system belongs to the weak type II superconductors was made by the authors as a result of erroneous calculations. In particular, the authors gave an estimate of the penetration depth $\lambda(0) = 3.8$ nm. For evaluating, they used the formula [20]

$$\lambda(0) = \frac{\Phi_0}{2\sqrt{2}\pi\, H_c \xi(0)}\,,$$

where, for the value of $H_{c2}(0)$, they used the second critical field estimated from transport measurements, instead of the thermodynamic critical field. These values, in general, can differ significantly. As an example, for niobium, the second critical field $H_{c2}(0)$ is approximately three times greater than the thermodynamic field $H_c(0)$. If we estimate $\lambda(0)$ (and then the Ginzburg–Landau parameter, $\kappa = \lambda/\xi$) from the formula

$$\lambda(0) = \sqrt{\frac{mc^2}{4\pi ne^2}}\,,$$

we obtain $\lambda(0) = 56$ nm, $\kappa = 50$, whence it follows that a material with such parameters is a hard type II superconductor, and, consequently, superconducting transitions in a magnetic field should be significantly broadened. The value $\lambda(0) = 56$ nm can be considered a lower estimate, and in

[13], for the parent compound H_3S, it was estimated $\lambda(0) = 188$ nm.

Let us now consider the problems associated with measuring magnetic properties of the C–S–H system. It was the magnetic data that drew the most criticism, and it was the magnetic data that was the officially announced reason for the publication's withdrawal. The publication presented several diamagnetic jumps in the temperature dependence of the susceptibility measured with alternating current using the 'crossed' coils technique. According to the authors, the data shown in the figures are the result of subtracting the 'background signal' (measured separately with a nonsuperconducting sample) from the 'measured voltage' (the authors' formulation). Neither the 'background signal' nor the 'measured voltage' was given in the original article, but only the result of the subtraction. After persistent criticism [14, 15], the authors posted tables with the data of the 'measured voltage' [21]. This made it possible to carefully check all the presented magnetic data. It turned out [16, 22] that in almost all cases the 'background signal' has noise identical to the noise of the 'measured voltage.' Such a coincidence of two independent random signals is practically impossible, because the authors argued that the measurements were made in different experiments, and, in this case, the noise in each measurement would be unique, not correlated in different measurements. The authors of [23] recognized this and changed their statement from the original work [5], but again did not provide a clear explanation as to why they had to resort to a 'user-defined procedure' instead of the generally accepted background signal subtraction procedure.

Thus, as was carefully analyzed and shown in [22], the published curves of the temperature dependence of the susceptibility cannot be considered reliable data for proving superconductivity in the C–S–H compound.

4. Conclusions

Let us now put together all the main facts regarding the publication on the C–S–H compound.

(1) The magnetic susceptibility data reported in the original article [5] cannot be considered reliable for asserting superconductivity in the C–S–H system. The authors did not use generally accepted scientific methods in data processing and did not provide raw data on susceptibility that would not contradict the general principles of statistics.

(2) The data on the resistance jump and the independence of the jump width from the magnetic field contain several internal contradictions and mean either that the C–S–H system is some kind of unique superconductor, unlike any other superconducting hydrides, or that the resistance jumps are not related to superconductivity.

(3) Theoretical work on the search for thermodynamically stable structures of the C–S–H system was not successful. Only H_3S systems with a very low level of carbon doping can have good stability. This contrasts sharply with the ratio of sulfur and carbon content declared by the authors as 1:1.

(4) No experimental group was able to repeat the results of this work.

Thus, after the withdrawal [6] of publication [5], we can say that superconductivity in the mysterious C–S–H system cannot be considered scientifically proven, and superconductivity at room temperature has not yet (alas!) been achieved.

It should also be noted that the journal *Nature* (occupying the leading position in the world ranking of scientific journals) not the first time showed tolerance for published materials that demonstrate the authors' clear desire for sensationalism, to the detriment of scientific reliability. The previous 7 papers withdrawn from this journal in 2003 were publications on the 'observation' of superconductivity in $CaCuO_2$, C_{60}, C_{70} fullerene single crystals, an organic polymer film, molecular crystals, etc. [24].

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