On the ac magnetic susceptibility of a room temperature superconductor: anatomy of a probable scientific fraud

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In Nature 586, 373 (2020) [1], Snider et al announced the experimental discovery of room temperature superconductivity in a carbonaceous sulfur hydride under high pressure, hereafter called CSH. The paper reported sharp drops in the measured magnetic susceptibility as a function of temperature for five different pressures, that were claimed to be a superior test signaling a superconducting transition. Here I present several arguments indicating that the susceptibility data published in [1] were probably fraudulent. This calls into question the validity of the entire paper and its claim of detection of room temperature superconductivity. I also describe the roadblocks that I have encountered in reaching this conclusion. A variety of implications of this situation are discussed.

I. INTRODUCTION

On October 14, 2020, the journal Nature published a paper [1] reporting the experimental discovery of the first room temperature superconductor. If this is true, it represents a major scientific breakthrough. In the ensuing months thereafter, scientists throughout the world have worked under the assumption that the published paper [1] is scientifically valid. In this paper I present reasons that cast strong doubt on this assumption and discuss a variety of implications.

Ac magnetic susceptibility is a superior test for superconductivity in all materials, including materials under high pressure [2–6]. A superconductor excludes magnetic flux, so upon cooling into the superconducting state a sharp drop in the ac magnetic susceptibility is observed. For experiments under high pressures, because of the smallness of the sample required by the geometry of the diamond anvil cell, the detected signal is a tiny drop in a large signal arising from the superposition of the sample and the background magnetic responses, with the background signal being several orders of magnitude larger than the sample signal [2, 3, 5, 7]. For that reason, it is customary to subtract from the total signal (the so-called "raw data") the background signal, according to the relation

$$data = raw\ data - background\ signal. \quad (1)$$

The background signal is usually obtained by measuring the susceptibility at a pressure value such that no superconducting transition occurs in the temperature range of interest [5].

The Snider et al paper [1] shows susceptibility data curves for five different pressures, three in their Fig. 2a and two more in Extended Data Fig. 7d. They are reproduced in Fig. 1 of this paper. In their caption to Fig. 2a, the authors inform the reader that "*The background signal, determined from a non-superconducting C-S-H sample at 108 GPa, has been subtracted from the data.*"

Ref. [1] does not present the raw data for those five measurements, nor the background signal at 108 GPa that was allegedly subtracted. This prevents the interested reader from critically evaluating the significance

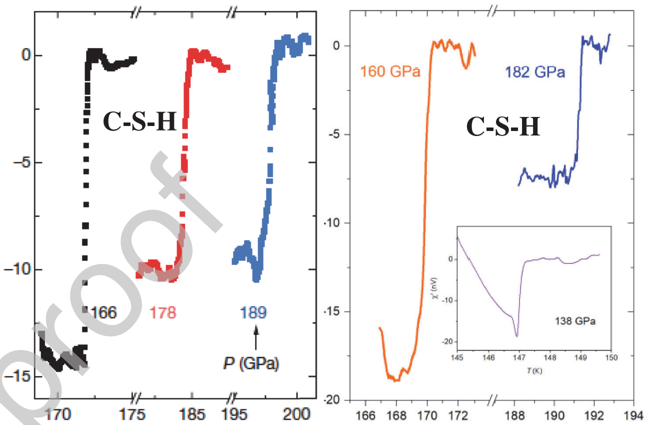

FIG. 1: ac susceptibility measurements on CSH, from ref. [1] Fig. 2a (left panel) and Extended Data Fig. 7 d (right panel). The horizontal axis is temperature in K, the vertical axis is nV [5]. The inset in the right panel shows raw data for pressure 138 GPa.

and validity of the data presented. It is a policy of the journal that published the paper, Nature, explicitly agreed upon by the authors in their "Data availability" statement, that such data should be available from the corresponding author upon reasonable request. The verbatim statement in the paper [1] is given here:

"**Data availability**: *The data supporting the findings of this study are available within the article and its Supplementary Information files, and from the corresponding author upon reasonable request.*"

I have requested the raw data and background signal data underlying the published data from the corresponding author Ranga Dias on November 12, 2020, and repeatedly thereafter, and not received them to date. In this paper I will: (1) explain the scientific justification for my data request. I will explain why (i) the published data strongly suggests that either the interpretation of the published results is wrong, and/or (ii) there were experimental errors, and/or (iii) there was manipulation of data. (2) I will describe what happened since I first requested the data till today, in particular the reasons for why I have not been able to obtain the data, and the roles that the journals Nature and Physical Review Letters and the National Science Foundation played in this; (3) I will argue that the facts strongly suggest that there was scientific fraud involved in [1]; (4) I will discuss implications of these facts in the broad context of the scientific enterprise.

II. THE PUBLISHED SUSCEPTIBILITY DATA FOR CSH

In addition to the five curves of susceptibility *data* shown in Fig. 1 above, the authors also published one curve of *raw data* measurements in the inset of their Extended Data Fig. 7 d, shown in the inset of the right panel of Fig. 1 above. The first peculiar fact to notice is that the raw data presented are for a pressure (138 GPa) different from (lower than) the five values of pressure for which susceptibility data were shown, namely 160, 166, 178, 182, 189 GPa. This makes it impossible for the reader to get information on the *background signal* using the raw data and Eq. (1). This fact alone points to an intent by the authors to hide relevant information, since it would have been equally easy for the authors to show the raw data for any one of the five pressure values for which they showed data, which would have at least revealed the background signal for that temperature range.

The raw data shown in the inset of Fig. 1 show nearly temperature independent behavior in a range of about 2K above the presumed superconducting transition at $T_c \sim 147K$, a sharp drop at T_c as the temperature is lowered, and a sharp rise below T_c where the susceptibility rises above the normal state level as the temperature is lowered by less than 2K below T_c, i.e. in a range that is less than 1.5% of T_c. This sharp rise below T_c is completely contrary to what is expected for a superconductor [2, 3, 5, 7]. The contribution to the raw data from the susceptibility of the sample is expected to be reflected in the sharp drop of the raw data at 147K as it undergoes the superconducting transition, but should remain at the lower value or change smoothly below T_c if the sample indeed underwent a transition to the superconducting state. So under that scenario, which is what ref. [1] assumes, the sharp rise of the raw data below T_c must reflect the behavior of the background and not of the sample.

However, it is difficult to imagine a realistic scenario under which the background susceptibility would undergo such a dramatic change in a narrow temperature interval around a temperature which happens to coincide with the temperature at which the sample goes superconducting. The slope of the curve shown in the inset of Fig. 1 is essentially zero above 147K, and has a large negative value (about 10nV/K) below 147K. We cannot assert that this is impossible, if for example a ferromagnetic transition were to occur in the background at a temperature slightly below 145K, the lowest temperature shown in the inset of Fig. 1. However, even under such

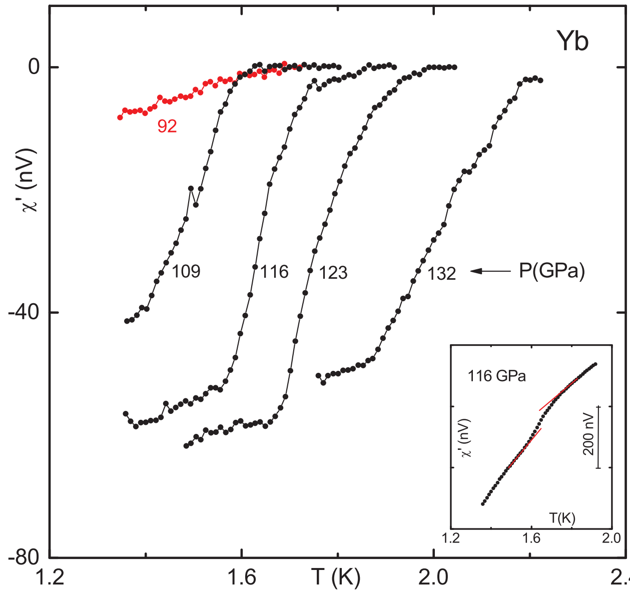

FIG. 2: Ac magnetic susceptibility of Yb under pressure ([7]). The inset shows raw data, from which the signal shown is extracted by substraction of a background signal.

an unlikely scenario, it would be impossible to assume that such a magnetic transition in the background also occurs at the five other values of temperature and pressure where drops in the data for magnetic susceptibility are shown in Fig. 1. Therefore this would imply that the raw data for the five curves shown in Fig. 1 looked qualitatively different from the raw data shown in the inset, in particular they did not show a sharp change in the slope right below the transition temperature. But if that was the case it would not make sense for the authors to have shown what would be highly atypical data, that they showed in the inset of Fig. 1. The logical purpose of showing one example of raw data out of a set of measurements would be to show a typical behavior.

An example of typical behavior of raw versus non-raw data of ac susceptibility is shown in Fig. 2 from ref. [7] by Song et al. The raw data show approximately the same slope above and below T_c, and the more rapid decrease around T_c signals the transition, which is seen more clearly in the curve in the body of the figure after the background of approximately constant slope is subtracted.

Consequently, assuming the data shown in the inset of Fig. 1 are real, we would have to conclude that the behavior shown by the raw data in Fig. 1, in particular the sharp rise in susceptibility below the sharp drop, reflects behavior of the sample rather than of the background. As already mentioned, this would be incompatible with the behavior expected for a superconductor, but could instead indicate that the sample is developing magnetic order, e.g. a transition to a ferromagnetic state. Such a transition has been predicted to occur for metallic hydrogen under high pressures [8, 9]. Under that scenario, the raw data for other pressures could look similar if the ferromagnetic transition shifts with pressure together with the susceptibility drop.

More likely however, we have to conclude that the highly atypical raw data shown in the inset of Fig. 1 do not reflect reliable measurements but instead either (a) inadvertent technical errors in the experiment or (b) scientific fraud. The fact that the authors of Ref. [1] over the last 9 months have declined to share the raw data and background signal associated with these measurements as well as to provide a possible explanation for this highly unusual behavior of their published data strongly suggests that (b) is the reality. Further evidence for it is provided in the next sections.

III. THE 53RD SUPERCONDUCTING ELEMENT

In 2009, Debessai, Matsuoka, Hamlin, Schilling and Shimizu reported in Physical Review Letters that Eu metal had become the 53rd known elemental superconductor in the periodic table [10, 11]. The result has not been independently reproduced to date but is generally assumed to be true [12–18].

Resistivity measurements presented in ref. [10] only showed small drops at some pressures. The conclusion of the paper [10] that Eu is a superconductor was largely reached on the basis of ac magnetic susceptibility measurements shown in Fig. 2 of ref. [10], reproduced here as Fig. 3. Indeed the sharp drops of nearly equal magnitude occurring at temperatures that change monotonically with pressure are indicative of a superconducting transition. The magnitude of the drop is expected to be given by the formula [5, 6]

$$S = \frac{\pi f \alpha H V N}{R(1-D)}\chi \qquad (2)$$

where f is the frequency and H the magnitude of the applied field, V is the volume of the sample, N is the number of turns in the pickup coil, R is the radius of the pickup coil, D is the demagnetization factor of the sample, and $\alpha = 1/\sqrt{1+(L/R)^2}$ with $2L$ the length of the coil. In these units, $\chi = -1$ for a superconductor. For frequency $f = 1023Hz$ and coil parameters used in the experiment expression (1) becomes [6, 10]

$$S(nV) = \frac{8.17\times 10^{-5} V(\mu m^3)}{1-D} \qquad (3)$$

For a cylindrical sample of diameter $80\mu m$ and height $15\mu m$ as used in the experiment [6, 10] $D \sim 0.671$ and Eq. (2) yields $S \sim 20nV$, consistent with what is seen in Fig. 3.

The reason that these issues are relevant to the topic of this paper is the remarkable similarity of the insets of Fig. 3 for Eu and Fig. 1 for CSH. Fig. 4 displays these insets next to each other. The temperatures in the

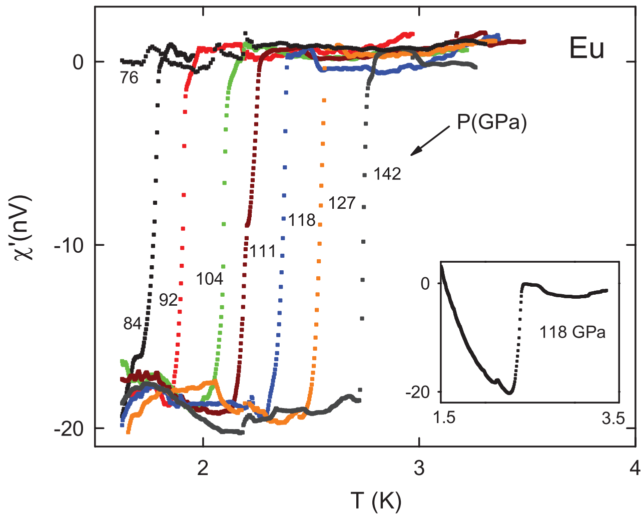

FIG. 3: From ref. [10], ac magnetic susceptibility of Eu under pressure versus temperature. The inset shows raw data for $118GPa$.

two cases differ by two orders of magnitude, the range of temperatures covered in the insets however is comparable, 5K for CSH and 2K for Eu.

Reference [1] (CSH) refers readers to ref. [6] for details of the ac susceptibility measurements, and so does ref. [10] (Eu). Reference [6] gives some technical details of the experimental setup and procedure and refers for other details (number of turns of the coils, radius and length of the pickup coil) to ref. [5]. So we conclude that Eq. (3) should apply to both the CSH and Eu cases. For CSH, the dimensions of the sample were estimated to be $80\mu m$ diameter and $5-10\mu m$ in thickness [1]. Therefore the sample thicknesess for the two cases [1] and [10] differed by a factor of up to 3. Yet the signal magnitude observed in the two cases was almost identical, $\sim 20nV$, as seen in Fig. 4. This is remarkable.

Even more remarkable is that the shape of the two curves is very similar. Both curves are nearly horizontal above the drop and rise steeply below the drop, to a value which is above the value of the signal above T_c, in a temperature range $\Delta T \sim 0.75K$ for Eu and $\sim 1.5K$ for

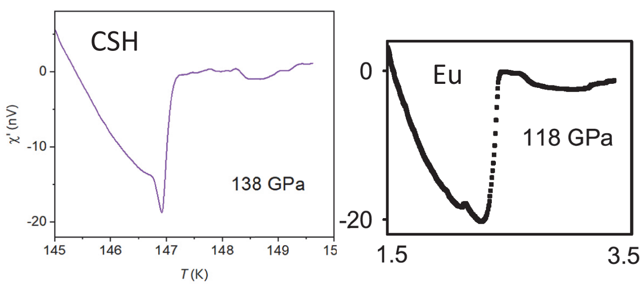

FIG. 4: Raw data for ac magnetic susceptibility of CSH [1] and of Eu [10] under pressure.

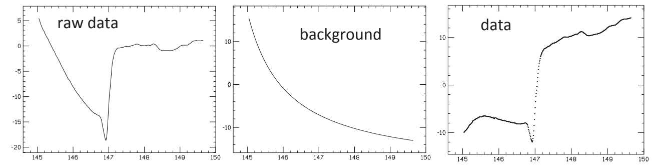

FIG. 5: Attempt at modeling the reported raw data for CSH. The left panel shows the reported raw data [1]. The middle panel shows an assumed background signal corresponding to Curie-Weiss behavior with Curie temperature 143.9K, i.e. only 2% away from the assumed superconducting $T_c = 147K$. The right panel shows the resulting data obtained from subtracting the background signal from the raw data, Eq. (1).

CSH. As discussed earlier, the steep rise below the drop is not expected for a superconducting sample, so it has to be a property of the background.

At the low temperatures studied in the case of Eu, such a rise is not very surprising, it can be attributed to Curie or Curie-Weiss behavior of the background. Note that the steep rise in the case of Eu is in a temperature range $\Delta T \sim 0.75K$ which is $\sim 30\%$ of T_c. Instead, for the case of CSH the rise occurs in a range of $\sim 1.5K$ which is only 1% of T_c. As argued in the previous section, this behavior is very unexpected.

To try to model this behavior in CSH, we have assumed a Curie-Weiss law for the background, as shown on the middle panel of Fig. 5. With that background, and the raw data given by the inset in the CSH paper, shown on the left panel of Fig. 5, the data would be given by the right panel of fig. 5. We note that the data would show an anomalous change in slope between above and below the jump, not seen in the other five data curves shown in Fig. 1. Furthermore, the background in the middle panel is obtained assuming a Curie-Weiss temperature 143.9K, rather close to the temperature where the jump occurs (147K). This is necessary to reproduce the large change in slope across the transition seen in the raw data while attempting to minimize the change in slope that would be due to the sample signal, where no such change is expected. We conclude from this analysis that we cannot find a plausible scenario under which the raw data presented in the CSH paper would reflect a superconducting transition without an artificially fine-tuned background signal, and even in that case the resulting data would look substantially different from the published ones.

To conclude this section, for reasons that will become clear later it is relevant to point out the following three facts: (i) According to the "Author contributions" statement of ref. [1] there were two authors that performed magnetic susceptibility measurements for the CSH paper, namely Ranga P. Dias (the corresponding author) and Mathew Debessai; (ii) M. Debessai is the first author of ref. [10] (Eu) and of ref. [6], to which both ref. [1] and [10] refer for details on the measurements; (iii) According to ref. [21], M. Debessai taught high pressure experiments to R. P. Dias.

The facts discussed above raised questions in my mind about the validity of the magnetic susceptibility measurements presented both for CSH [1] and for Eu [10]. I wrote and published a paper raising these questions in late 2020 [19, 20]. Other developments are discussed in the forthcoming sections.

IV. INITIAL ATTEMPTS TO OBTAIN RAW DATA FOR CSH

As explained it the previous section, the published ac susceptibility data are not themselves measured. Rather, they are the difference between two measured quantities, the raw data and the background signal, both much larger than their difference. It is only natural that in order to assess the validity and veracity of the published data and their claimed implications, a reader should have access to the measured data. If those measured data are not available in a data repository, authors have an ethical and moral obligation to make the measured data available to whoever wants to examine them.

Indeed, that is the stated policy of both publication venues and research funding agencies. Nature magazine, that published ref. [1], states in their website [22]: *"A condition of publication in a Nature Portfolio journal is that authors are required to make materials, data, code, and associated protocols promptly available to readers without undue qualifications."* The US National Science Foundation (NSF), that funded the research reported in refs. [1] and [10] states in their website [23]: *"Investigators are expected to share with other researchers, at no more than incremental cost and within a reasonable time, the primary data, samples, physical collections and other supporting materials created or gathered in the course of work under NSF grants. Grantees are expected to encourage and facilitate such sharing."*

To begin to understand the significance of the reported CSH susceptibility data I contacted the corresponding author, R. Dias, on October 25, 2020 by email, and asked him what was the value of the frequency used in the ac susceptibility measurements, that is not given in ref. [1], which is a crucial vaue that determines the magnitude of the signal according to Eq. (2). Not receiving a response, I repeated my inquiry on October 29. On October 29 Dias responded declining to provide the requested information. On November 7, I wrote to M. Debessai asking for that information. On November 8, Debessai informed me that the frequency used had been 1023 Hz.

Subsequently on the same November 8, I wrote again to M. Debessai requesting more information on details of the CSH susceptibility measurements and requesting the raw data for the susceptibility data shown in the CSH paper. On November 10, Debessai sent me an email giving some additional information on the measurements, but not including the requested raw data. Furthermore 54 minutes later, Debessai sent another email stating *"Debessai, Mathew T would like to recall the message"* that had been sent 54 minutes earlier.

On November 12, I sent to Dias copy of the information request that I had sent to Debessai earlier, requesting from Dias this information including the raw data. I repeated my request to Dias on November 13, asking for all the raw data.

Also on November 13, I wrote to the Nature Editor that had been in charge of processing the CSH paper, Dr. Tobias Roedel, and asked him if he could help me get the information I had requested from Dias. On November 15, Dr. Roedel wrote to Dias stating *"Please send the raw data on the susceptibility measurements in your room temperature superconductivity paper to Jorge Hirsch (in copy of this email). I attached the request below."*

On November 15, Dias responded to me with copy to Dr. Roedel, stating:

"We acknowledge your request for data relating to our recent Nature article entitled "Room temperature Superconductivity on carbonaceous sulfur hydrides." We have discussed the request with counsel, and unfortunately, we are not able to provide you with the data/information for a number of reasons, including the following. First, the data may contain patentable inventions for which patent applications have not been updated or filed. We have been advised that disclosure of the data may impair our ability to file patent applications in the future. We cannot anticipate when we may have the authorization to share the data. Second, given the fact that you have an active comment on our work, we consider such a request would not be reasonable."

The 'active comment' referred to above, by F. Marsiglio and myself, was submitted to Nature and to the arXiv preprint server on October 19 and posted on arXiv on October 20 2020 [24], and was at that time under consideration for publication by Nature. The comment addresses the unusual behavior of the resistivity data for CSH in the absence and in the presence of an applied magnetic field reported in ref. [1].

It is also relevant to this story that independently Dr. Evgueni F. Talantsev had requested resistivity raw data as well as a a time track record for each measurement from Dias directly and through Nature editor Dr. Luke Fleet on October 21, 2020 [25] and again directly and through Nature editor Dr. Roedel on or about November 10 [26]. On November 16, Dias responded [27]:

Dear Dr. Talantsev,

We acknowledge your request for data relating to our recent Nature article entitled "Room temperature Superconductivity on carbonaceous sulfur hydrides". We have discussed the request with counsel and unfortunately, we are not able to provide you with the data for a number of reasons, including the following. The data may contain patentable inventions for which patent applications have not been updated or filed. We have been advised that disclosure of the data may impair our ability to file patent applications in the future. We cannot anticipate when we may have the authorization to share the data.

Regards,

Ranga

The comment that Frank Marsiglio and I had submitted to Nature on October 19 was subsequently accepted for publication (with some modifications) and published by Nature on August 25, 2021, 310 days after submission [28]. In the intervening time Frank Marsiglio and I published four papers in other journals with faster processing times discussing various reasons of concern on the validity of the data for CSH as well as other hydrides [29–32]. Dogan and Cohen also published a paper raising similar questions about the validity of the CSH paper [33]. All of this occurred many weeks and months before *any* questioning of the CSH paper appeared on the pages of Nature.

V. INITIAL ATTEMPTS TO OBTAIN RAW DATA FOR EU

In early November 2020 I corresponded with two of Debessai's coauthors of ref. [10] explaining my concern with the published Eu and CSH susceptibility data and asking whether I could obtain from them the susceptibility raw data for the Eu paper [10]. They both informed me that they had not performed the measurements themselves and they both suggested that I ask M. Debessai for the raw data. On November 14, I wrote to Debessai asking him whether he had the raw data for the 2009 Eu paper [10] and if so to please send them to me. On November 16 I wrote to him again and suggested to have a zoom meeting to discuss these issues. On November 23 Debessai responded that we could have a zoom meeting, and we had the meeting on November 24 2020.

In the zoom meeting on November 24, Debessai confirmed that he had performed the susceptibility measurements on both CSH and Eu, and explained to me many of the details and difficulties associated with such measurements. I explained to Debessai my concerns with the data published for both CSH and Eu and reiterated my request for the raw data for both experiments. Debessai responded that he would retrieve the raw data for both CSH and Eu and reexamine them and get back to me to schedule another zoom meeting to go over the raw data and share them with me.

That was the last direct communication I had from M. Debessai until the present.

VI. SUBSEQUENT ATTEMPTS TO OBTAIN RAW DATA FOR CSH

In view of Dias' November 15 response to my request for data, declining to provide the requested information, I wrote again to Dr. Roedel on November 16, 2020, asking whether Nature had any specific policy for a situation like this where authors decline to supply supporting information alleging patent considerations. I also explained that in my view that was just an excuse. I asked Dr.

Roedel whether Nature would consider requesting that the authors retract the paper given their unwillingness to provide supporting information. I also asked Dr. Roedel whether he had any suggestions concerning this matter.

Dr. Roedel did not respond to my email.

Seven months later, on June 21, 2021, I wrote to Nature's Editor in Chief, Dr. Magdalena Skipper, with copy to Dr. Roedel, again requesting help to obtain the requested susceptibility data, and requesting that Nature takes some action if the authors continue to refuse to share the data. Dr. Skipper has not responded to my email to date. On June 28, Dr. Roedel informed me that *"We are discussing internally and with the authors and will inform you as soon as possible about any new developments."*

On July 8, 2021, I submitted for publication in Nature a "Matters Arising" paper explaining my concerns with the published susceptibility data for CSH and the inaccessibility of the raw data. On July 12, Dr. Roedel informed me *"I regret to say that we cannot offer to publish it."*

On July 19 2021 I inquired with Dr. Roedel again about the availability of the requested raw data. On July 20, Dr. Roedel informed me that he *"had a call with the authors and they are discussing with their legal counsel."* I responded to Dr. Roedel on July 20 explaining again that there are no patent issues associated with the raw data I am requesting, and suggesting that he checks this fact with any expert working in the field. On July 28 Dr. Roedel informed me *"The authors informed us on the weekend that they are denying your request for additional data. We are now discussing internally on our further course of action."*

As of today, August 25, 2021, more than 10 months after the CSH paper was published, Nature has taken no public action. On the pages and websites of Nature there is absolutely no information for readers that it is not possible to get any data supporting the Nature publication [1] from their authors. To the best of my understanding this is in flagrant violation of Nature's stated data availability policy [22, 34]. It specifies that [34] Nature will publish an "Editor's Note", (*"An Editor's Note is a notification alerting readers if the journal has initiated an inquiry in response to concerns raised about a published article."*) and subsequently an "Editorial Expression of Concern" (*"Editorial Expression of Concern: An Editorial Expression of Concern is a statement from the editors alerting readers to serious concerns affecting the integrity of the published paper."*) in such situations. None of that has happened so far, more than 9 months after both Talantsev and I first requested supporting data through Nature.

VII. SUBSEQUENT ATTEMPTS TO OBTAIN RAW DATA FOR EU AND ULTIMATE SUCCESS

On November 19 and November 21, 2020, I sent a copy of my paper [19] commenting on the Eu paper [10] to three of Mathew Debessai's coauthors, asking for comments. One of them responded *"I don't think it is appropriate to level such a serious accusation against Debessai"*, another responded that I *"create with the reader the impression that Mathew may have manipulated the data"* and *"I am very disappointed and more than a little angry. Your Comment contains numerous errors and misrepresentations"*, but unfortunately did not specify what the errors and misrepresentations were. A third coauthor responded that my paper *"points to important issues"*.

I submitted my paper [19] to Physical Review Letters as a Comment on ref. [10]. On December 4, PRL Editor Saad Hebboul informed me that *"we are unable to consider this manuscript for publication in Physical Review Letters."* I immediately submitted it to Physica C, where it was processed at lightning speed, accepted on December 8 and published on-line on December 10 2020 [20].

I also submitted my paper to the arXiv preprint server on November 25, where it was put on hold with no explanation, as has happened with nearly all my individual submissions to arXiv in the last 5 years, and finally posted 20 days later, on December 15, 2020 [19].

My goal in sending my paper [19] to Physical Review Letters as a Comment on ref. [10] was to elicit a Reply from the authors that would address and hopefully explain the issues I was raising. In view of PRL's decision to reject my Comment, I wrote to all the authors of ref. [10] on December 5 2020, attaching a copy of my paper, informing them that PRL had declined to publish it, informing them of my intention to attempt to publish it in another journal, and inviting them to reply to me addressing the points raised in the paper as well as suggesting that they consider writing a paper addressing these issues and that they repeat the experiment. I received no response from any of the authors. On February 28, 2021, I wrote again to the five authors expressing my disappointment at not having received a response and expressing my hope to learn more about these issues from them. Again I received no response from any of the authors.

On July 6, 2021, I wrote to two of Debessai's coauthors of ref. [10], expressing again my disappointment at not having received any information on the concerns I had raised on the Eu paper and not having obtained the raw data for the measurements reported in ref. [10]. On July 10th, I wrote to them again informing them that in view of this situation it was my intention to communicate my questions and concerns to the OIG (Office of the Inspector General) at NSF, that deals with *"allegations or suspicions of fraud, waste, abuse, mismanagement, research misconduct (fabrication, falsification, plagiarism), or unnecessary government expenditures."* [35]

On July 11, 2021, the senior author of ref. [10] informed me that the day before he had located the raw data for Eu that I had requested. On July 16, 2021, I finally received the raw data for Eu, 244 days after I first requested them.

VIII. ANALYSIS OF THE EU RAW DATA

James Hamlin provided to me on July 16, 2021 the raw data for the Eu measurements [10] as well as the laboratory notebook recording those measurements, and gave me essential explanations necessary to understand that information. I am grateful to James and to the other authors of ref. [10] that played a role in making this happen for these actions.

In the days that followed I examined that information and came to the definite conclusion that the susceptibility data published in Fig. 2 of ref. [10] (Fig. 3 in this paper) were not an accurate representation of the data that had been collected. Instead, that substantial alteration and manipulation of the measured data had taken place, contrary to proper scientific practice, with the goal to provide the reader with a convincing case for superconductivity of Eu, when in fact the measured data did not support such a conclusion.

In the following I provide three examples of data alteration and manipulation in the Eu paper [10].

A. Example 1

Figure 6 illustrates how the measured raw data for one pressure were altered and manipulated to arrive to the published inset in Fig. 2 of [10]. To begin with, the pressure for this measurement was 120 GPa according to the lab notebook, but Fig. 2 of ref. [10] says it was 118 GPa. The measured data, shown in the red curve on the left panel of Fig. 6, are contained in the file titled 102108m3.dat. As can be seen, the magnitude of the jump is approximately twice as large as the published curve, shown by the blue curve on the left panel of Fig. 6. When the red data are scaled by a factor of 0.48, the center panel results. Next, the measured data are shifted horizontally by 0.1K, and now they coincide with the published data, as shown on the right panel of Fig. 6. Neither the scaling nor the shifting has any physical justification nor is it described in the paper. Recall that the amplitude of the jump is expected to be represented by the expression Eq. (2).

B. Example 2

The raw data underlying Fig. 2 of [10] were a subset of all the measurements performed in the time period October 2, 2008 to October 28, 2008. On each day, several

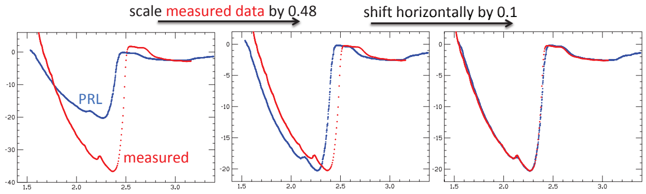

FIG. 6: Left panel: measured (red) and published (blue) raw data for susceptibility at 118 GPa. In the center panel, the red curve was scaled by a factor 0.48, in the right panel it was in addition shifted by -0.1K in the horizontal direction.

runs at a single pressure were obtained, with the pressure value indicated in the lab notebook. Each data file was named according to the date it was measured, and the run number was indicated by $m\#$. For example, file 100208m3.dat file (02m3 in short) contained the data obtained on the third run (hence m3) on October 2, 2008. Whether the data were obtained on warming or cooling was indicated on the lab notebook. Only warming runs were selected for the published data.

The background signal that was subtracted from the raw data was obtained from the average of the warming runs 100208m3.dat and 100308m2.dat, corresponding to pressures 47.63 GPa and 63.04 GPa, pressure values at which no superconducting transition was expected.

In Fig. 7, I picked one warming run for each value of the pressure, subtracted the background signal and plotted the results versus temperature. Fig. 7 illustrates what Fig. 2 of [10] (Fig. 3 in this paper) should have looked like. It can be seen that several curves in Fig. 7 show more than one jump, and that several jumps are larger than the jumps shown in Fig. 3 by a factor of more than 10. To illustrate that the particular runs chosen for Fig. 7 were not anomalous, I show in Fig. 8 all the warming runs for one value of the pressure, 142 GPa. It can be seen that they are qualitatively similar, and qualitatively different from the 142 GPa curve of Fig. 3, which shows a single jump of magnitude $\sim 20nV$. Recall that the magnitude of the jump has physical significance as given by Eq. (2).

If Fig. 2 of ref. [10] would have looked like Fig. 7, it could not possibly have been published as evidence supporting superconductivity in Eu. Many of the jumps in Fig. 7 are of magnitude much too large to be associated with superconductivity. The fact that many curves show two jumps is inconsistent with the interpretation that they signal superconducting transitions. Even if one wanted to interpret only the small jump in Fig. 8 as signaling a superconducting transition, the fact that its magnitude varies by a factor of 3 between different runs would invalidate that interpretation.

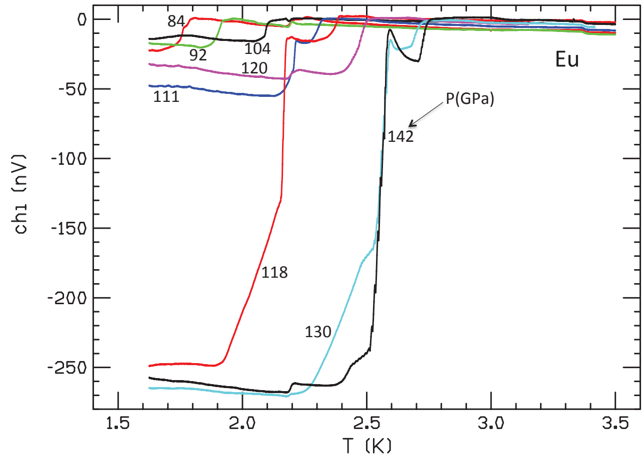

FIG. 7: Real part of ac susceptibility versus temperature for Eu metal as pressure is increased from 84 to 142 GPa. One warming run for each pressure was selected from the raw data, then the background signal was subtracted.

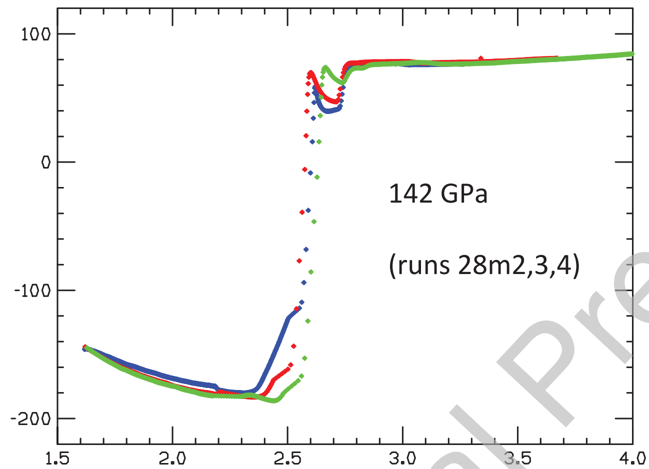

FIG. 8: All the warming runs obtained from the raw data for pressure 142 GPa. The horizontal axis shows temperature in K and the vertical axis shows real part of the ac susceptibility in nV. The vertical shift relative to the data shown in Fig. 7 has no physical significance.

C. Example 3

A variety of transformations were used to go from the measured data to the published data. Here I illustrate some of them. I am grateful to James Hamlin for sharing his insights with me on this issue, which he uncovered, without which I would have been unable to perform this analysis.

Fig. 9 shows on the right panel the curve published in Fig. 2 of [10] as the results for 118 GPa after background subtraction. The left panel shows the results of actual measurements (file 0820m2.dat) after subtraction of the background signal, the average of files 0802m3.dat and 0803m2.dat. The inset of the left panel shows the part

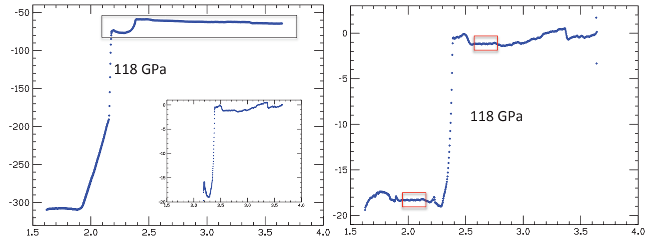

FIG. 9: The right panel shows the published curve for 118 GPa. The left panel shows the measurements for 118 GPa (file 102008m2.dat) after background subtraction. The inset of the left panel shows the part of the curve enclosed in the rectangle after subject to the transformation chinew=chi+46.842+4.836T. Note that the inset on the left panel looks identical to the upper part of the curve on the right panel.

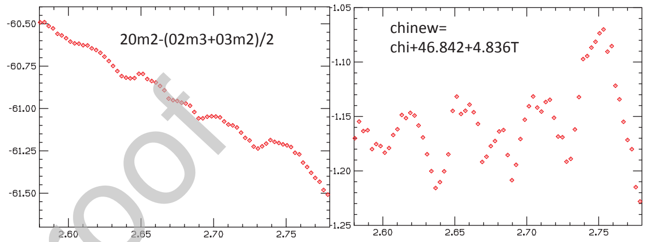

FIG. 10: The left panel shows the result of subtracting the background signal from the raw data, restricted to the small temperature interval 2.58K to 2.78K. The right panel shows the same data after the linear transformation Eq. (4).

of the curve enclosed in the rectangle after subject to the transformation

$$chinew = chi + 46.842 + 4.836T. \quad (4)$$

Note that it looks identical to the upper part of the curve in the right panel (the published curve).

Where did the lower part of the curve on the right panel of Fig. 9 come from? Clearly not from the measured data on the left panel. It turns out that at least part of it was copied and shifted from the upper part of the curve.

The left panel of Fig. 10 shows the data from the curve on the left panel of Fig. 9 for the small range of temperature 2.58K to 2.78K, and the right panel shows the same data after subject to the linear transformation Eq. (4). It turns out that those data are identical to a small part of the lower part of the curve on the right panel of Fig. 9, between 1.95K and 2.15K. That part is enclosed in a red rectangle on the right panel of Fig. 9. Fig. 11 shows on the left panel the data between 1.95K and 2.15K and on the right panel those data shifted horizontally by 0.63K, and vertically by 17 nV, superposed to the data from the right panel of Fig. 10. It can be seen that the data from these two different temperature ranges (1.95K,2.15K) and (2.58K,2.78K) coincide after these shifts.

To summarize this example: the published data in Fig.

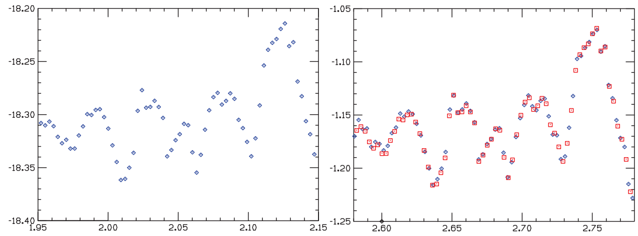

FIG. 11: The left panel shows the data from the temperature range (1.95K,2.15K) (curve enclosed by the lower rectangle on the right panel of Fig. 89 The right panel shows the superposition of those data with the data from the right panel of Fig. 10, corresponding to the curve enclosed by the upper rectangle on the right panel of Fig. 9.

2 of ref. [10] for 118 GPa resulted from (i) taking part of the measured data and applying to them the linear transformation Eq. (4), (ii) discarding a large part of the measured data, (iii) copying and pasting part of the data onto other regions of the curve by horizontal and vertical shifts, and (iv) other unknown procedures. None of these procedures (i), (ii), (iii) has *any* physical justification, nor is the fact that these procedures were used disclosed in the paper.

The evidence of Examples 1, 2 and 3 discussed above establish unequivocally that extensive data alteration and manipulation occurred in going from measured data to published data for Fig. 2 of [10]. Fig. 2 of [10] was the crucial evidence presented in support of the conclusion that Eu was superconducting at these pressures and temperatures. It is clear that this conclusion was reached through scientific fraud.

And there is in fact additional evidence in the raw data indicating that the jumps in the signals obtained in raw data are unrelated to superconductivity, namely that they appear roughly equally in both real and imaginary parts of the measured susceptibility. This is inconsistent with the behavior seen in superconductors, which is that the imaginary part shows a peak where the real part shows a jump [36].

IX. THE ROLE PLAYED BY THE NATIONAL SCIENCE FOUNDATION

The research reported in the CSH paper [1] was funded by the US National Science Foundation under grant DMR-1809649, as the paper informs in its acknowledgements. On May 7, 2021, I contacted Dr. Tomasz Durakiewicz, the NSF Program Manager for that grant, by email. I informed him that I had been unable to obtain supporting data that I had requested from the authors of ref. [1], and that the journal where the work was published (Nature) had not been able to help. I also told him that I did not think the reason given by Dr. Dias for refusing to share the data, potential implications for patents, was applicable. I explained to Dr. Durakiewicz the reasons for why I was interested in those data. I asked Dr. Durakiewicz whether he could intervene and request that Dr. Dias sends me the requested magnetic susceptibility data in compliance with his obligations as an NSF-funded researcher, or else to advise me whether I should direct this request to a different person at NSF and if so to whom. I also called to Dr. Durakiewicz's attention my paper on Eu and CSH [20] where I explained why I was concerned about the published CSH susceptibility data.

Not having received any indication from Dr. Durakiewicz that he would act on my request, 25 days later on June 1, 2021 I wrote to Dr. Linda Sapochak, DMR Division Director, with the same query. On June 8, Dr. Sapochak responded requesting that I send her the original request that I had sent to Dr. Durakiewicz, which I immediately did.

On July 6, 2021, Dr. Sapochak informed me that according to Article 42 of the NSF-Specific Requirements to the Research Terms and Conditions, section b of the same allows exceptions to accommodate legitimate interests of investigators. She also explained that *"The PI has declared intent to share the data you requested once the associated pending patents are finalized and approved."*, and said she would be happy to discuss further with me if I had questions. However, the latter never took place despite my many attempts to do so.

I immediately responded to Dr. Sapochak's email saying that I did have further questions and would appreciate to discuss this with her at her earliest convenience. I pointed out that NSF Article 42b specifies that exceptions to the data sharing policy may be allowed only "where essential" "to accommodate legitimate interests of investigators". So I asked her to inform me on what grounds it had been determined that the interests accommodated are legitimate and the exception is essential to accommodate those interests for this case, and informed her that I didn't believe that was the case. I also pointed out that according to the PI's declaration quoted above, if patents are never finalized or never approved, the PI wouldn't have an obligation to share the data, which doesn't make sense.

Dr. Sapochak didn't respond to these points, and despite my repeated requests she never agreed to talk with me to discuss these questions. I also requested to talk with Dr. Durakiewicz repeatedly and was denied that opportunity. I suggested that they consult with experts in the field whether raw data and background signal for magnetic susceptibility mesurements could under any circumstance constitute "patentable inventions". No response.

On July 6, I explicitly told Dr. Sapochak about my concern that scientific fraud had been committed and that this was the reason for the refusal of the authors to share the data. On July 19 Dr. Sapochak responded *"With respect to your second issue of possible fraud, this is a matter involving PIs and Journal Editors and NSF does not get involved in resolving such disputes."*

As I was not getting responses I also sent copies of emails to Dr. Sean L. Jones, head of the NSF Directorate for Mathematical and Physical Sciences, and to Dr. Sethuraman Panchanathan, director of the U.S. National Science Foundation. It all fell on deaf ears.

Given this situation, on July 26 I contacted the Office of Inspector General (OIG) associated with NSF, which *"is responsible for promoting efficiency and effectiveness in agency programs and for preventing and detecting fraud, waste, and abuse. By statute, the NSF OIG is independent from the agency."* I again explained that I needed access to research data obtained under NSF funding, and that neither the authors nor the journal nor the NSF had been able to obtain the data. I also explained that "I have reason to believe that the research published by PI Ranga Dias in Nature 586, 373 (2020) does not properly reflect the findings resulting from the NSF-funded research." I also said that I would be happy to provide additional information and work with OIG to get this resolved.

One day later, on July 27, an anonymous email from OIG responded *"After careful consideration, our investigative staff determined that this matter is not appropriate for investigation by our office. We will take no action."*

I wrote again to OIG on July 27 and August 2 questioning their decision and offering reasons for it. I told them specifically that I have evidence suggesting that the reason the authors of ref. [1] refused to share their data obtained through research funded by NSF was to cover up fraud. OIG responded on August 11 that:
"Dr. Sapochak exercised her discretion as Deputy Director, Division of Materials Research to conclude Dr. Dias's data warranted an exemption from NSF's expectation of sharing data. There is no NSF requirement that she consult experts when making her decision. She did not violate any NSF policy in making her decision."
and
"We consider this matter closed."

Further emails by me to OIG on August 11 and August 17 went unanswered.

X. ANALYSIS OF THE CSH SUSCEPTIBILITY DATA

The CSH susceptibility curves shown in Fig. 1 do not show a lot of detail, and as discussed above I have been unable so far to obtain the data from the authors of [1], as well as the underlying raw data and background signal used to obtain those data. While I wait to get that information, it is possible to obtain some more information by analyzing the vector graphics image embedded in the published figure to extract the data points [37, 38], by using computer software such as inkscape and adobe illustrator. Figure 12 shows the data for pressure 166 GPa plotted with the resolution shown in the CSH paper and with higher resolution.

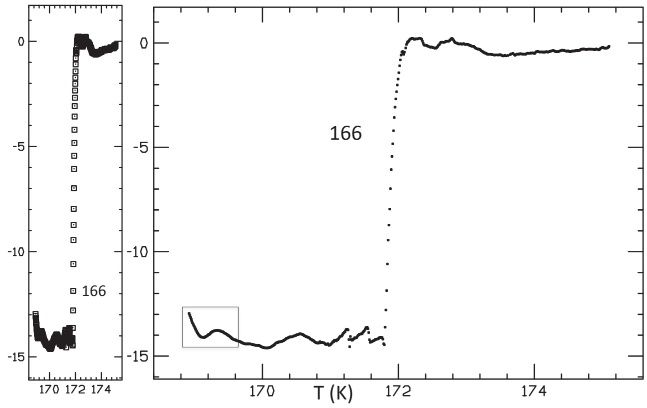

FIG. 12: Susceptibility data for CSH at 166 GPa plotted with the resolution of ref.. [1] and with higher resolution.

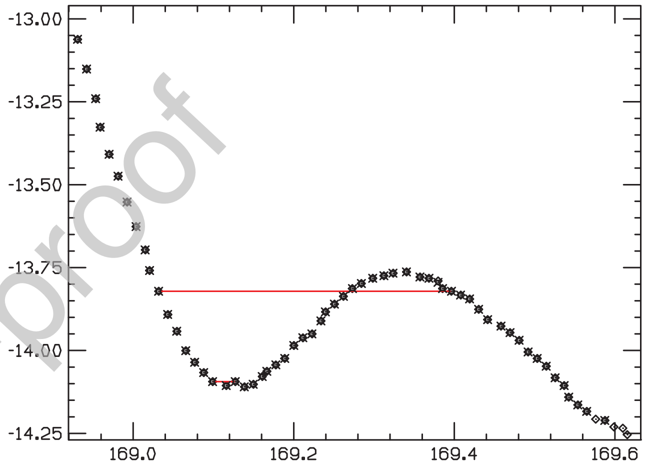

FIG. 13: The left part of the susceptibility curve of Fig. 12 (enclosed in the rectangle in Fig. 12) plotted with higher resolution. The two red lines connect points that show the same value of susceptibility to 6 digits accuracy.

Fig. 13 shows the low temperature tail end of the curve of Fig. 12 with higher resolution. The two red lines connect points that have the same value of susceptibility *to 6 significant figures.*

There are many other such coincidences for the curve at this pressure as well as the curves for other pressures. Fig. 14 shows the susceptibility data for pressure 189 GPa, and Figs. 15 and 16 show a portion of those data showing many such coincidences.

Finally, in Fig. 17 we show results for the *increment* in the susceptibility $\Delta\chi'$ for two subsequent data points versus temperature. The colored lines connect points that coincide to 6 decimal places *in absolute value.* There are cases where they have the same sign and others where they have opposite sign. Many more such coincidences exist, only the ones with largest values are shown in Fig. 17.

These data were supposedly obtained by experimentally measuring the ac susceptibility of the sample plus

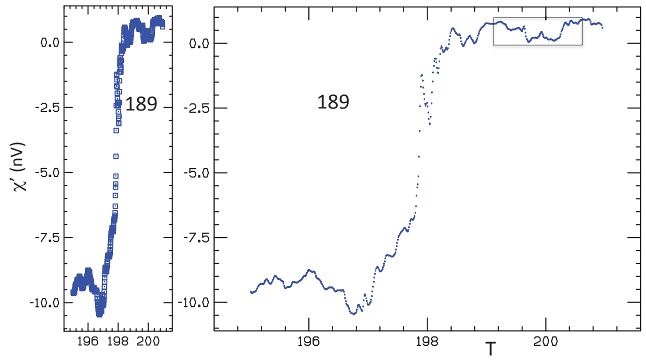

FIG. 14: Susceptibility data for CSH at 189 GPa plotted with the resolution of ref.. [1] and with higher resolution.

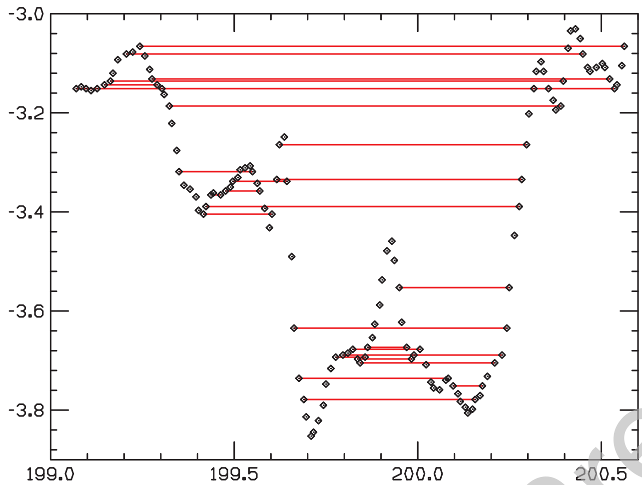

FIG. 15: Part of the susceptibility data for CSH at pressure 189 GPa (enclosed in the rectangle in Fig. 14), showing many points for which the susceptibility is the same to 6 digits accuracy, connected by red lines. There is one case of seven points on the same red line, for which the susceptibility is the same to 6 digits accuracy, shown in more detail in Fig. 16.

background (raw data) and separately measuring the background signal at a different pressure, and subtracting according to Eq. (1). I don't understand how after subtracting these two independent measurements the resulting data can show the coincidences to 6 decimal places shown in Figs. 13-17.

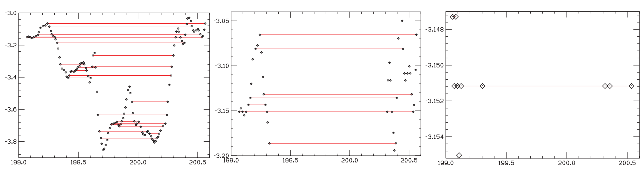

FIG. 16: The left panel is the same as Fig. 15, the center and right panels show the same range of temperature values and increasing resolution in the susceptibility. The right panel shows the seven points that are identical to 6 digits accuracy.

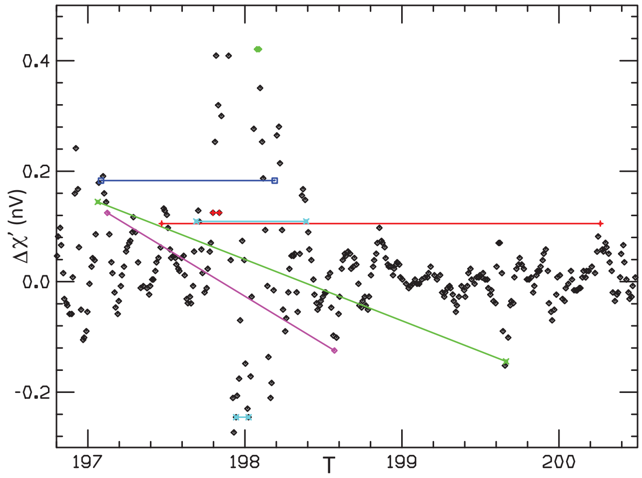

FIG. 17: Difference in subsequent values of the susceptibility for 189 GPa plotted in fig. 14 versus temperature. The colored lines connect values of this difference that are identical in absolute value to 6 decimal figures.

I suggest that one possible explanation is that it is the result of data manipulation and alteration such as was described in Sect. VIII for Eu. If there is another explanation it will hopefully become apparent from examination of the data and raw data supplied by the authors once that happens.

XI. IMPLICATIONS FOR CSH

With the information I have at this point in time I cannot prove beyond reasonable doubt that fraud was involved in the production of the published ac susceptibility curves for CSH. Here I would like to summarize the reasons discussed in this paper for why I believe that such a scenario is highly probable:

(1) The authors of the CSH paper ref. [1] have repeatedly refused to provide any access to the raw data and background signal measured that were used in the production of their published susceptibility curves, alleging nonexistent patent reasons.

(2) The behavior of the raw susceptibility data published for CSH is highly unusual, as discussed in Sect. II, and nobody has offered any explanation for it.

(3) The raw susceptibility data published for CSH look almost identical to the raw data for Eu published in ref. [10], for very different materials and for temperature ranges differing by two orders of magnitude. I pointed this out in a paper published back in December 2020 open access [19, 20]. In addition I called that paper to the attention of the two authors of [1] responsible for the CSH susceptibility measurements (Debessai and Dias) many months ago (December 2020 and March 2021 respectively), asking for comments and an explanation. Neither of them responded.

(4) M. Debessai measured and processed the data that

resulted in the published susceptibility data for Eu, and either alone or in conjunction with R. Dias measured and processed the data that resulted in the published susceptibility data for CSH. M. Debessai taught R. Dias high pressure experiments [21], years after Debessai published ref. [10].

(5) The results for the susceptibility of Eu published in 2009 [10] are established now to be fraudulent [39]. The authors of ref. [10] have informed Physical Review Letters on July 27, 2021 that they may retract the paper [40].

(6) Analysis of the vector graphics images of the susceptibility data for CSH published in [1] show unexpected coincidences suggesting data manipulation, as discussed in Sect. X.

It would be easy for the authors of the CSH paper to establish that their published susceptibility results are valid and real by providing their raw data for examination. They have not done so despite repeated requests, nor have they provided any justification for their allegation that providing those data would infringe on their patent rights.

XII. BROADER IMPACTS

Since the time that ref. [1] was published in Nature, October 14, 2020, the scientific community has been under the impression that the long-sought goal of room temperature superconductivity has finally been achieved [1, 41]. Many scientists throughout the world have been devoting intense efforts, resources and time for many months since that date under the belief that the information published in the Nature paper reflects true results of measurements and is not the result of data alteration and/or manipulation. If such data alteration and/or manipulation did occur, the fact that the scientific community has not been aware of it for many months has caused important damage to the scientific enterprise.

As just one example of the degree to which room temperature superconductivity in CSH is taken to be an established fact, the US National Science Foundation issued a call for proposals in January 2021 titled "Funding Opportunity - Light and Warm Superconductors" [42]. Its opening paragraph reads *"Recent advances in achieving room temperature superconductivity under pressure offer new challenges and lead to new fundamental questions. Motivated by predictions based on theory and computation, record high temperature superconductivity in hydrogen rich compounds has been discovered continuing a trend of increasing highest transition temperatures."* Grants on proposals submitted in response to this call have already been awarded.

Publication venues and research funding agencies have policies in place that claim to require that researchers publishing in those venues and being funded by those agencies share the data underlying their research results upon reasonable request. However, if those policies are not enforced they are worthless.

In this paper I have presented information to the effect that both the journal Nature and the US National Science Foundation have failed to enforce those policies for the case at hand for many months. This suggests that they are not likely to enforce those policies in other cases either. I suggest that this attitude of Nature and NSF is very detrimental to the scientific enterprise. The fact that they claim in their websites and documents to require such data sharing but in practice don't enforce those requirements is deceptive to scientists that believe the information presented in those websites and documents is faithful.

To the extent that researchers can publish results without being obligated to supply supporting data if so requested, the scientific enterprise is impacted in a profoundly negatively way. Other scientists rely on published data assuming that they are valid, and if the published information is fraudulent their efforts and resources are wasted.

If scientists can successfully claim that they are exempted from requirements to provide supporting data to their published results alleging patent rights, when there is no reasonable justification for such allegation, without even having to provide an explanation for why that would be the case, as happened in this case, then something is very wrong. It should be obvious that scientists that have something to hide are the ones that are most likely to invoke exception clauses to avoid sharing their data. Therefore those scientists should be subject to the highest scrutiny. Their alleged reasons for exemptions should be analyzed and external expert opinions should be sought to assess whether there is validity to them or not, particularly if they are challenged by the person making the data request, as happened in this case. To say (as OIG told me, see Sect. IX) that *"Dr. Sapochak exercised her discretion"*, *"There is no NSF requirement that she consult experts when making her decision. She did not violate any NSF policy in making her decision."* as a justification for not doing so should not be an acceptable explanation. An NSF policy should be put in place if there is not one already to make such discretionary behavior by an NSF official to be in violation of NSF policy.

Few researchers are interested and motivated to spend time and effort examining whether colleagues committed scientific fraud. Naturally they are, as I am, more interested in advancing their own research goals. For that reason, there should be procedures and regulations in place that make it difficult for scientists to commit undetected fraud. Such provisions exist on paper, but from what I have experienced and discussed in this paper it should be evident that they are not enforced, neither by the most high profile journals nor by the preeminent research funding agency. So they are worthless in their current form. I hope this paper will contribute to changing this situation. NSF should take seriously allegations of scientific fraud and not dismiss them without examination. I told both NSF and OIG that I had evidence suggesting that the CSH NSF-funded research was fraudulent, and both NSF and OIG-NSF declined to investigate my allegation.

Special mention is merited by the Office of Inspector General associated with NSF, supposedly "independent from the agency". OIG is tasked with providing *independent* oversight of the agency's programs and operations, is responsible for promoting efficiency and effectiveness in agency programs and for preventing and detecting fraud, waste, and abuse [43]. Their website states *"You can help the Office of Inspector General (OIG) improve management and eliminate fraud by providing information to OIG about allegations or suspicions of fraud, waste, abuse, mismanagement, research misconduct (fabrication, falsification, plagiarism), or unnecessary government expenditures."* They are supposed to *"Investigate fraud, misuse of funds, and other violations of laws and regulations."* However for the case at hand, they dismissed the information I provided them about suspected research misconduct without *any* investigation or followup.

And yet it is interesting and ironical to note that it was my mentioning that I would report to OIG that the authors of the 2009 Eu paper were not sharing their data with me what prompted the authors to share their data with me (see Sect. VII of this paper). This is akin to homeowners putting up signs on their front lawn "Beware of the dog" or "Premises protected by monitored alarm" when in fact there are neither dogs nor alarm systems on the premises. The difference is, those homeowners don't pay salaries to nonexistent dogs and alarm monitors. I suggest this should be considered by those worrying about"unnecessary government expenditures".

XIII. CONCLUDING REMARKS

An avalanche of experimental and theoretical papers have been published since 2015 that report that high temperature superconductivity in hydrogen-rich materials is a reality [44]. However, I argue that whether or not that is a true fact remains an open question, despite the generalized belief to the contrary. Several recent papers have called that belief into question [24, 28–33] challenging the accepted interpretation of the existing experimental evidence.

If it is established, as suggested in this paper, that the measured experimental data on susceptibility of CSH were altered and manipulated to arrive at the published data and hence the published data do not faithfully reflect the measured data, as has been established to be the case for Eu, the validity of all the other experimental data published in the CSH paper will be questionable. This will invalidate its claim that room temperature superconductivity in CSH has been demonstrated, and suggest that room temperature superconductivity in CSH does not exist.

The reason for the generalized belief that high temperature superconductivity should exist in hydrides under high pressure is the universal faith in BCS theory [45] as giving the correct description of superconductivity in many real materials. Experiments will eventually decide for a fact whether hydrides under pressure are or are not high temperature superconductors. For this to happen sooner rather than later it is important that researchers with the ability to contribute to settle this question keep in mind the possibility that BCS theory may not be the correct theory to describe superconductivity in any real material, as I have repeatedly suggested [46]. If it is found that superconductivity does not exist in hydrides, that possibility will become much more likely. If it is established that it does exist, the alternative theory that I have proposed will be proven wrong [47].

The path that goes from omitting to include in a scientific paper observations or results of calculations that seem contrary to preconceived conclusions, to outright manipulation and alteration of data or calculations to support preconceived conclusions, is a slippery slope. The temptation to do so is high, and even highly reputable scientists have been accused to be guilty of such behavior [48]. In cases where the preconceived conclusion is scientifically correct, such instances are likely to often remain undetected and unsuspected. In cases where it is not, they are more likely to eventually come to light. The blind faith in a generally accepted theory will make such instances of improper scientific conduct more likely. Time will tell what is the reality in the case under consideration here.

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