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News & Highlights

Controversy Clouds Real Progress in Superconductor Research

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In the 8 March 2023 issue of the journal *Nature*, a paper attracted global attention with the report of a new superconductor material exhibiting ground-breaking properties [1,2]. A group led by Ranga P. Dias, assistant professor of mechanical engineering at the University of Rochester (Rochester, NY, USA), described a hydride material that superconducted at around room temperature, albeit at pressures 10 000 times greater than atmospheric pressure [3].

Superconducting materials can carry an electrical current with no resistance, hence without losing energy as heat. Existing superconductors have proved particularly useful for building powerful electromagnets, which are essential in magnetic resonance imaging (MRI) scanners and large particle accelerators (Fig. 1). But there is a catch. Most of these materials can only superconduct at extremely low temperatures, which requires costly coolants and complex engineering, limiting their applications. Physicists view room-temperature superconductors as a "Holy Grail," an almost magical prize that could revolutionize power grids, transportation, and more. Practical room-temperature superconductors would dramatically reduce the cost of producing and operating powerful electromagnets. Such materials might even be used to carry electricity over long distances without energy loss, and to create highly efficient electric motors.

Regardless, experts in the field judged the results reported by Dias et al. too good to be true. This was not the first time that a claim of a room-temperature superconductor from the Dias' group faced doubts. In 2022, *Nature* retracted a 2020 paper from Dias et al. that also reported such a material [4,5]. The doubts about the more recent paper proved merited when *Nature* retracted it in November 2023 after a majority of Dias' co-authors raised concerns about the authenticity of its findings [6,7].

Unfortunately, the paper from Dias' group was not the only superconductor claim that attracted controversy in 2023. The storm surrounding these controversies, as well as previous ones, has obscured real progress in the superconducting materials field in recent years. "The hunt for the Holy Grail has distracted us from all the other good things going on in this area," said Chris J. Pickard, professor of materials science at the University of Cambridge (Cambridge, UK). Researchers have uncovered entirely new families of superconducting materials, some of which superconduct at temperatures not much colder than a domestic refrigerator—although only under intense pressures. Meanwhile, Pickard said, computational simulations and machine learning are increasingly helping researchers fine-tune these materials to further improve their performance.

Scientists discovered superconductivity more than a century ago but did not figure out how it worked for almost 50 years [8]. When the atoms in a superconductor's lattice vibrate, the jiggling herds electrons together to form so-called Cooper pairs. In this union, large numbers of electrons can glide through the material without bumping into its atoms, enabling a resistance-free flow of current. But heat can easily tear apart Cooper pairs, and so standard superconductors only perform when cooled below their very cold critical temperatures. The superconducting magnets in an MRI scanner, for example, typically contain niobium–titanium cooled to just 4 K with liquid helium.

In contrast, so-called high-temperature superconductors can perform above 77 K, the temperature of liquid nitrogen, which is an easier-to-handle and much less expensive coolant than liquid helium, potentially enabling a wider range of applications. Scientists discovered the first high-temperature superconductors, copper-based materials called cuprates (Fig. 2(a)), in the 1980s. A series of advances pushed their critical temperatures up to 133 K in 1993 [9]. But progress stalled in part because the cuprates'

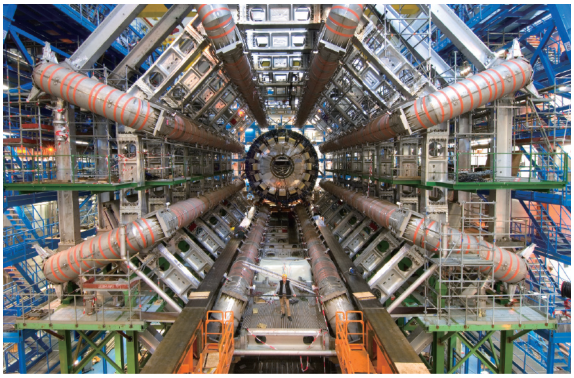

Fig. 1. Particle accelerators like the Geneva, Switzerland-located European Organization for Nuclear Research (CERN) Large Hadron Collider control the trajectories of charged particles using huge superconducting magnets, such as the eight superconducting coils seen here. Practical room-temperature superconducting materials could dramatically reduce the cost and complexity of such giant magnets. Credit: CERN (public domain).

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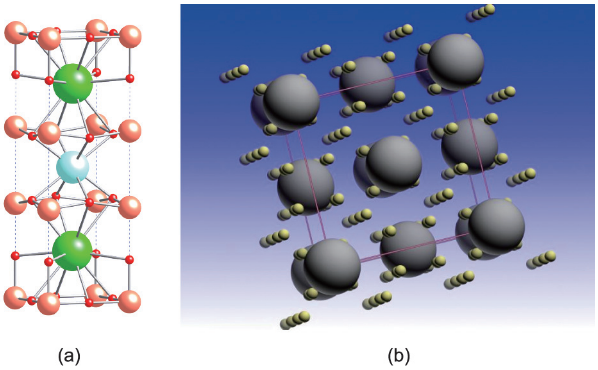

Fig. 2. Example structures of superconducting cuprates and hydrides. (a) The cuprate material yttrium barium copper oxide (pink: Cu; red: O; green: Ba; light blue: Y) was the first material to demonstrate superconductivity at the temperature of liquid nitrogen. (b) At high pressures, hydride superconductors such as lanthanum hydride (gray: La; yellow: H) can superconduct at about 250 K. Credits: (a) Ben Mills/Wikimedia Commons (public domain); (b) courtesy of Drozdov et al. (public domain).

Cooper pairs form in a different way than in conventional superconductors. Physicists lacked a reliable theory that could direct them how to further improve the materials, said Lilia Boeri, associate professor of theoretical condensed matter physics at the Sapienza University of Rome, Italy. Still, several companies now produce superconducting cables that incorporate cuprates, which are chilled by a cooling core of liquid nitrogen [10]. But cuprates are generally brittle and expensive, which restricts their use [10].

More recently, physicists have been excited about superconductors based on iron and nickel, which share some similarities with cuprates and may help researchers understand unconventional superconductivity [11]. But none of these materials has surpassed the critical temperatures of the best cuprates.

Cuprates remained the champion superconductors until the discovery of the hydrides in the 2010s. Hydrogen atoms in the atomic lattice of these materials can vibrate at very high frequencies, which boosts the strength of the Cooper pair coupling, keeping them together at much warmer temperatures. The caveat is that the hydrogen atoms need to be pushed together to form a kind of metallic state for this effect to emerge. Reaching that metallic state requires extraordinarily high pressures, like those found at the Earth's core.

In 2015, Mikhail Eremets, a group leader at the Max Planck Institute for Chemistry (Mainz, Germany), and colleagues found that a sulfur hydride (H_3S) could superconduct at 203 K if it was put under 145 GPa of pressure in a specialized kind of device known as a diamond anvil cell [12]. Four years later, Eremets' team found that lanthanum decahydride (LaH_{10}) could superconduct at about 250 K and 170 GPa, a record-high critical temperature (Fig. 2(b)) [13].

The intense pressures needed rule out using such materials in practical applications. But unlike cuprates, hydrides are conventional superconductors that are well described by theory, which makes researchers optimistic that they can improve on the already promising results. Some scientists are now working to reduce hydride operating pressures, while others are figuring out ways to raise their critical temperatures still further, perhaps even to room temperature. "High-temperature superconductivity at ambient pressure would revolutionize the world," said Eremets.

So, there was widespread excitement in 2020 when Dias et al. [4] unveiled research showing that a compound of carbon, sulfur, and hydrogen could superconduct at 288 K—essentially room temperature—and 267 GPa. As mentioned previously, *Nature* retracted that paper in 2022 after doubts emerged about the reliability of key data it reported [5].

Then the report from Dias et al. in 2023 [3] claimed that a nitrogen-doped lutetium hydride material superconducted at 294 K and just 1 GPa. In short order, however, other researchers' independent efforts to replicate the new result failed. Meanwhile, theorists' calculations suggested that the material simply should not be able to exist under such conditions, let alone superconduct [14]. "People were extremely skeptical of this result," said Boeri, who investigated the claims with Pickard and others. After the paper was retracted, an investigation by *Nature*'s journalism team revealed evidence that Dias had fabricated data in the paper [15,16]. The community has now completely discounted Dias' work, Boeri said, and the University of Rochester has stripped Dias of students, teaching responsibilities, and access to his laboratory [15].

While the Dias scandal unfolded, an even more astounding claim emerged from a start-up company, called Quantum Energy Research Centre, in Seoul, the Republic of Korea. In July 2023, the company's team led by Sukbae Lee and Ji-Hoon Kim claimed to have made a material from copper, lead, phosphorus, and oxygen that superconducted at atmospheric pressure and temperatures up to 400 K [17,18].

The material, dubbed LK-99, immediately drew skepticism from superconductivity researchers who quickly proved that impurities in the material probably caused the reported signs of superconductivity, including magnetic levitation and abrupt changes in resistance [18,19]. Researchers also found that the pure form of the material was in fact an insulator, ruling out superconductivity [20]. However, some scientists are still hopeful that the claim contains useful clues about how to achieve room-temperature superconductivity. A pair of research teams in China, for example, reported in January 2024 that there were hints of superconductivity in a material very similar to LK-99 [21].

There are differing views about the impact of these troubling events on the field. Eremets called the Dias scandal a "disaster," and worried that it would prompt funding agencies to become warier about supporting work on hydrides. About the LK-99 episode, though, Boeri was more sanguine. "I do not think it has had a particularly negative impact," she said. "In a way, it has had a positive effect, because it made people more aware that this sort of research exists."

Those who look beyond the recent controversies will find that superconductivity research has experienced a period of sustained success (Fig. 3) [22]. Over the past two decades, theoretical structure prediction has improved dramatically, enabling researchers to calculate electron energies and other key properties used to predict whether materials might be high-temperature superconductors. These calculations give experimental scientists valuable pointers about which materials they should be making and testing. Their results then feed back into the theory and modeling of superconductors, further honing simulations. "There is a really good synergy between theory and experiment," said Eremets. "This drives the field forward enormously."

For example, in a preprint released on 11 October 2023, Pickard and his colleagues unveiled calculations suggesting that a magnesium iridium hydride material should be able to superconduct at 160 K and ambient pressure [23]. Their work also proposes a feasible, albeit challenging, way to make the material in the laboratory. Bolstering the case for the material, in a preprint released just a day before, on 10 October 2023, a team led by Antonio Sanna and Miguel A. L. Marques at the Max Planck Institute of Microstructure Physics (Halle, Germany) independently predicted that the same material should be a high-temperature superconductor [24].

Pickard estimates that it may eventually be possible to find a hydride that superconducts at about 200 K and ambient pressure [25]. Lowering the pressure needed to make hydrides

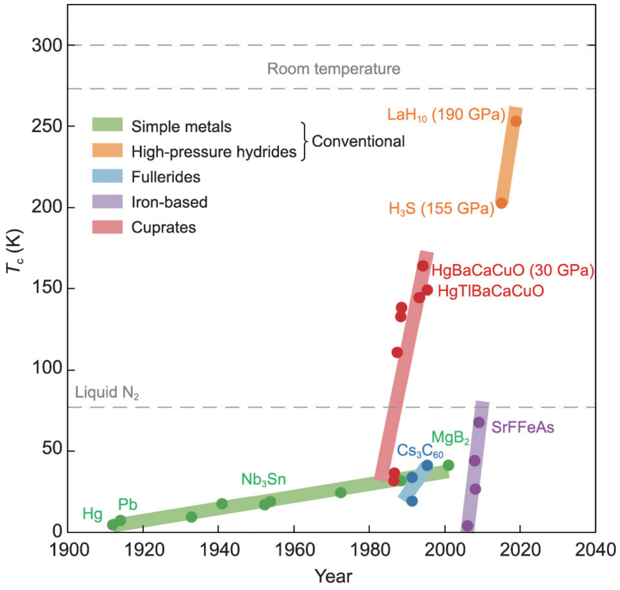

Fig. 3. After a surge of progress on cuprate superconductors in the 1980s and 1990s (red), physicists turned their attention to iron-based superconductors (purple) and then high-pressure hydrides (orange), reaching unprecedented operating temperatures close to room temperature. T_c: critical temperature (temperature necessary for superconducting properties). Credit: Ann Rev Condens Matter Phys (with permission).

superconduct would not only bring practical applications closer to realization but also help to stimulate further research by making it more accessible, Pickard said. Today, only a few laboratories like Eremets' have the specialist equipment and expertise needed to create and study materials at immense pressures. Lower operating pressures would allow many more researchers to join the hunt, making it easier to find new superconductors, and to verify the startling claims that keep coming, Pickard said. "If you can get it close to ambient pressures, it completely opens up the scrutiny that the field can be put under."

References

[1] Chang K. New room-temperature superconductor offers tantalizing possibilities [Internet]. New York City: The New York Times; 2023 Mar 8 [cited 2024 Apr 11]. Available from: https://www.nytimes.com/2023/03/08/science/room-temperature-superconductor-ranga-dias.html.

[2] Service RF. Superconducting crystal may be 'revolutionary'. Science 2023;379(6636):966–7.

[3] Dasenbrock-Gammon N, Snider E, McBride R, Pasan H, Durkee D, Khalvashi-Sutter N, et al. Retracted article: Evidence of near-ambient superconductivity in a N-doped lutetium hydride. Nature 2023;615:244–50.

[4] Snider E, Dasenbrock-Gammon N, McBride R, Debessai M, Vindana H, Vencatasamy K, et al. Retracted article: Room-temperature superconductivity in a carbonaceous sulfur hydride. Nature 2020;586:373–7.

[5] Snider E, Dasenbrock-Gammon N, McBride R, Debessai M, Vindana H, Vencatasamy K, et al. Retraction note: Room-temperature superconductivity in a carbonaceous sulfur hydride. Nature 2022;610:804.

[6] Jin CQ, Ceperley D. Hopes raised for room-temperature superconductivity, but doubts remain. Nature 2023;615:221–2.

[7] Dasenbrock-Gammon N, Snider E, McBride R, Pasan H, Durkee D, Khalvashi-Sutter N, et al. Retraction note: Evidence of near-ambient superconductivity in a N-doped lutetium hydride. Nature 2023;624:460.

[8] Heike Kamerlingh Onnes facts [Internet]. Stockholm: Nobel Prize Outreach AB; c2024 [cited 2024 Apr 11]. Available from: https://www.nobelprize.org/prizes/physics/1913/onnes/facts/.

[9] Schilling A, Cantoni M, Guo JD, Ott HR. Superconductivity above 130 K in the Hg–Ba–Ca–Cu–O system. Nature 1993;363:56–8.

[10] Rahman A, Rahaman Z, Samsuddoha N. A review on cuprate based superconducting materials including characteristics and applications. Amer J Phys Appl 2015;3(2):39–56.

[11] Li D, Lee K, Wang BY, Osada M, Crossley S, Lee HR, et al. Superconductivity in an infinite-layer nickelate. Nature 2019;572:624–7.

[12] Drozdov AP, Eremets MI, Troyan IA, Ksenofontov V, Shylin SI. Conventional superconductivity at 203 kelvin at high pressures in the sulfur hydride system. Nature 2015;525:73–6.

[13] Drozdov AP, Kong PP, Minkov VS, Besedin SP, Kuzovnikow MA, Mozaffari S, et al. Superconductivity at 250 K in lanthanum hydride under high pressures. Nature 2019;569:528–31.

[14] Ferreira PP, Conway LJ, Cucciari A, Di Cataldo S, Giannessi F, Kogler E, et al. Search for ambient superconductivity in the Lu–N–H system. Nat Commun 2023;14:5367.

[15] Garisto D. Superconductivity scandal: the inside story of deception in a rising star's physics lab. Nature. In press.

[16] Garisto D. Exclusive: official investigation reveals how superconductivity physicist faked blockbuster results. Nature 2024;628:481–3.

[17] Lee S, Kim J, Kim HT, Im S, An S, Auh KH. Superconductor $Pb_{10-x}Cu_x(PO_4)_6O$ showing levitation at room temperature and atmospheric pressure and mechanism. 2023. arXiv:2307.12037.

[18] Guo K, Li Y, Jia S. Ferromagnetic half levitation of LK-99-like synthetic samples. Sci China Phys Mech Astron 2023;66:107411.

[19] Zhu S, Wu W, Li Z, Luo J. First order transition in $Pb_{10-x}Cu_x(PO_4)_6O$ ($0.9 < x < 1.1$) containing Cu_2S. 2023. arXiv:2308.04353.

[20] Puphal P, Akbar MYP, Hepting M, Goering E, Isobe M, Nugroho AA, et al. Single crystal synthesis, structure, and magnetism of $Pb_{10-x}Cu_x(PO_4)_6O$. 2023. arXiv:2308.06256.

[21] Wang H, Yao Y, Shi K, Zhao Y, Wu H, Wu Z, et al. Possible Meissner effect near room temperature in copper-substituted lead apatite. 2024. arXiv:2401.00999.

[22] Pickard CJ, Errea I, Eremets MI. Superconducting hydrides under pressure. Annu Rev Condens Matter Phys 2020;11:57–76.

[23] Dolui K, Conway LJ, Heil C, Strobel TA, Prasankumar RP, Pickard CJ. Feasible route to high-temperature ambient-pressure hydride superconductivity. 2023. arXiv:2310.07562.

[24] Sanna A, Cerqueira TFT, Fang YW, Errea I, Ludwig A, Marques MAL. Prediction of ambient pressure conventional superconductivity above 80 K in hydride compounds. 2023. arXiv:2310.06804.

[25] Shipley AM, Hutcheon MJ, Needs RJ, Pickard CJ. High-throughput discovery of high-temperature conventional superconductors. Phys Rev B 2021;104(5):054501.