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Hunting for the Next High-Temperature Superconductor

Sam Lemonick

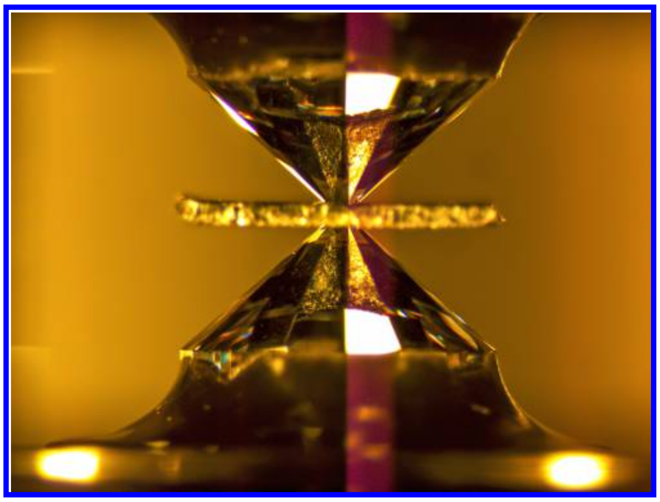
Scientists employ computational and experimental tools to explore whether hydrides could form stable superconductors.

Brian Skinner remembers getting back from a weekend bachelor party and hearing about the paper. "Everyone was talking about it," says Skinner, a postdoc at Massachusetts Institute of Technology. It was posted on the physics preprint server arXiv and described a silver-and-gold nanostructured material that acted as a superconductor at 236 K, or −37.15 °C, and ambient pressure.

That claim was remarkable. Superconductors are materials with zero electrical resistance, meaning an electrical current flows through them with no energy loss. They're used to produce the powerful electromagnets in magnetic resonance imaging and nuclear magnetic resonance machines, as well as in particle accelerators. Existing superconductors, however, work at very low temperatures. The superconducting niobium−titanium wires used in many MRI machines sit in a 4 K (−269 °C) bath of liquid helium, for instance. A material that acted as a superconductor at ambient temperatures (closer to 293 K) and pressures could revolutionize electric transmission and power storage and enable energy-efficient vehicles that move with little friction by hovering on magnetic tracks, among many other proposed applications.

The arXiv paper, from Anshu Pandey and Dev Kumar Thapa of the Indian Institute of Science, set off a furious rush in physics laboratories around the world to replicate the results. The excitement didn't last long. Skinner noticed and publicized inconsistencies in one of the group's data plots. The source of those inconsistencies is still unknown. Pandey and co-workers have said they intend to recheck their results and will issue new information when they have it.

No matter the source of the inconsistencies, physicists seem to agree that they'll need to see more data before they get too excited—or devote too many resources—to these supposed superconductors.



In a diamond anvil such as this one, two diamonds squeeze a cell filled with a material. At high pressures, certain materials could become superconductors. Credit: Steven D. Jacobsen.

Room-temperature, ambient-pressure superconductors may still be more science fiction than reality. But a pair of arXiv papers published a month after Pandey and Thapa's suggest a more promising direction in the hunt for a room-temperature—if not ambient-pressure—superconductor. Physicist Mikhail Eremets of the Max Planck Institute for Chemistry announced that his group had observed superconductivity in a lanthanum hydride material at 215 K. Two days later, at the American Chemical Society national meeting in Boston, and in a separate paper, Russell Hemley of George Washington University described superconductivity in a different lanthanum hydride at 260 K. Either would be a record, though neither finding has been confirmed by the most rigorous measurements of superconductivity or been peer-reviewed.

What's more, both groups observed the superconductivity at pressures between 150 and 200 gigapascal, 3 orders of magnitude greater than ambient pressure. So these are not practical room-temperature superconductors.

But scientists are still paying attention. "I'm excited," says Roald Hoffmann, a Nobel laureate and chemist at Cornell University who has worked with Hemley on other hydride superconductors. Hoffmann and others in the field think

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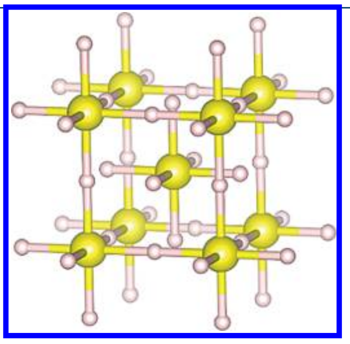
hydrides are a promising class of materials that could lead to superconductors at mild conditions. Experimentalists and theoreticians are working together to explore this family of materials.



H_3S holds the current record for a high-temperature superconductor. Sulfur is yellow and hydrogen is pink. Credit: Mikhail Eremets.

Sulfur hydride, H_3S, is the current record holder for high-T_c superconductors, as they're known. T_c refers to the critical temperature below which the material is a superconductor. In 2015, Eremets reported superconductivity in the material at 203 K and 90 GPa.

Scientists have a good reason for hunting for high-T_c superconductors among materials with an abundance of hydrogens. In 1968, Cornell University physicist Neil Ashcroft predicted atomic metallic hydrogen would be a superconductor at or above room temperature. Materials like metallic hydrogen are known as Bardeen−Cooper−Schrieffer, or BCS, superconductors, which are based on a theory developed by John Bardeen, Leon Cooper, and John Robert Schrieffer in the 1950s. In a metal like mercury, electrons will flow through a lattice of positively charged metal atoms. Above the critical temperature—in mercury's case, about 4 K—the lattice atoms vibrate. Electrons crash into the atoms, transferring energy that is lost as heat. That's the source of electrical resistance.

Below mercury's T_c, the atoms are motionless, allowing a different effect to take over. Each electron distorts the lattice slightly as it moves, creating what are called phonons. These regions of positive charge attract other electrons, creating pairs of electrons that—in a way—drag each other through the metal, eliminating resistance. Metallic hydrogen's lattice would consist of protons, which have a high charge density and high vibrational frequencies that would enhance this effect and lead to superconductivity at high temperatures, according to Ashcroft's predictions.

Ashcroft calculated that metallic hydrogen's T_c could be between 200 and 400 K. The problem is no one has definitively made a solid metal of atomic hydrogen. Scientists predict that very high pressure is needed to force hydrogen atoms to move out of diatomic molecules and into a lattice of protons and mobile electrons. Isaac F. Silvera and Ranga Dias of Harvard University reported in 2017 that they had made solid metallic hydrogen under 495 GPa of pressure. Eremets and others have dismissed these results, arguing that the measurements did not prove the team had made the elusive substance. Not long after announcing their discovery, Silvera and Dias revealed their original sample had disappeared, and they would need to repeat the experiments.

With metallic hydrogen still seemingly out of reach, it's fortunate that Ashcroft predicted another high-T_c superconductor class. In 2004, he argued that alloys with high hydrogen content would behave similarly to metallic hydrogen. That prediction set off an ongoing race to predict, synthesize, and test hydride materials.

Scientists theorize that silicon, lithium, and other hydrides could be high-T_c superconductors, but the list of synthesized hydride superconductors is still short. Eremets's sulfur hydride beat the previous record holder—a ceramic made of mercury, barium, calcium, copper, and oxygen—by more than 50 K. The Eremets group used a diamond anvil to produce the high pressures needed. The process is exactly what it sounds like: Two diamonds attached to a press squeeze a cell bounded by a metal gasket. The researchers piped hydrogen sulfide gas into the precooled cell and monitored the resistance in the sample as they increased the pressure. The cell is only about 25 μm wide, narrower than a strand of hair, which makes detecting resistance difficult. But Eremets's group was able to do it and measure magnetic susceptibility, which is the gold standard for proving superconductivity.

Interestingly, Eremets's team noticed two critical temperatures at which resistance dropped to zero, indicating a superconductor. The first occurred at 100 GPa and 60 K. The researchers saw a second at 150 GPa and 190 K but later revised the temperature up to 203 K. The group speculated that it had found two new high-T_c superconductors: H_2S and, after a pressure-induced chemical change, H_3S.

Thomas Timusk, a physicist at McMaster University who has worked with Eremets to confirm sulfur hydride superconductivity, says the discovery was really 2-fold. "It was a high-temperature superconductor, and it was a whole family of new superconductors," Timusk says, referring to hydrides. But the hunt for other members of that family has been slow going. Hoffmann recalls the rush of reproduction experiments after cuprate superconductors were discovered in 1986. "When they were first synthesized, within a week or two the experiment was reproduced in 20 labs," he recalls.

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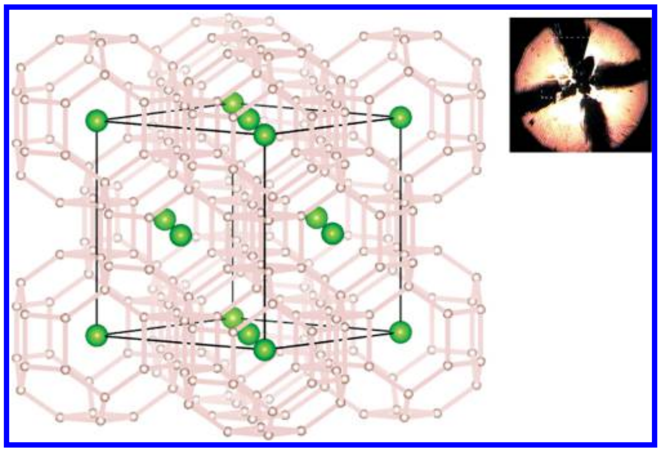
Scientists identified dozens of other cuprates in the following years. On the other hand, Hoffmann says, "H_3S took a year for another lab to replicate," and several years later only a couple of laboratories have managed it.

Still, researchers have made progress. Hemley, Hoffmann, Ashcroft, and colleagues predicted in 2017 several lanthanum and yttrium hydride superconductors that could have critical temperatures near or even above room temperature. Hemley and colleagues reported experimental confirmation of one of those, LaH_{10}, in their August arXiv paper and ACS meeting presentation.



Hydrogen atoms dominate the structure of LaH_{10} (left). Lanthanum is green and hydrogen is white. A sample of superconducting LaH_{10}, seen through a diamond anvil, sits centered among four black electrodes in a 50 μm wide cell (top right). Credit: Russell Hemley.

Hemley explains that the work started with a computational search for stable rare-earth metal hydrides with about 10 or more hydrogens per metal atom. His group then synthesized LaH_{10} by heating lanthanum metal with a laser in the presence of ammonia borane, which served as a source of hydrogen. Finally, the researchers measured the material's conductivity to confirm it was a superconductor. All this was done inside a diamond anvil cell like the one Eremets used. Hemley has not yet done the more rigorous magnetic susceptibility experiments to confirm superconductivity in LaH_{10}, but resistance measurements of several samples show it is a superconductor at 260 or 280 K and 190 GPa.

In these hydrides, scientists use sulfur, lanthanum, and other elements to destabilize the H_2 bond and push the hydrogen atoms into a metallic state. Hemley likens this effect to how increasing the pressure on a material enables superconductivity—it controls the distance between atoms and, in turn, the properties of the bulk material. When describing the effect of using bigger atoms to push hydrogen around, scientists sometimes use the phrase "chemical pressure," Hemley says. "You can think about chemical pressure and physical pressure working in the design of new materials."

Eremets published his own lanthanum hydride results at nearly the same time as Hemley. His group did not do the same X-ray diffraction measurements that Hemley did to determine it had made LaH_{10}, so Eremets's papers describe its material only as LaH_x. The researchers also found slightly different values than Hemley: a T_c of 215 K at 150 GPa. So it's possible that Eremets's group has made a different lanthanum hydride. In fact, Hemley also cautions that he may have made other materials in addition to or instead of LaH_{10}.

Even if the progress on hydrides has been slow, Timusk and others see these achievements as the success of a new approach for finding high-T_c superconductors. Eva Zurek, a computational chemist at the University at Buffalo, explains that the high pressures needed to make these hydride superconductors make it difficult for experimentalists to find new high-T_c superconductors on their own. "Experiments in high pressure are very hard," Zurek says, so theoreticians need to help guide researchers on where to look so they aren't wasting time in the lab. Chemists' theoretical understanding of what makes a material a high-T_c superconductor is still limited, but Zurek says scientists are starting to see trends in the structures and compositions of stable, high-T_c superconducting hydrides, and many of them look like the sulfur, lanthanum, and yttrium hydrides that Hemley, Eremets, and others are developing.

The field also hopes that this work will eventually lead to a high-T_c superconductor that's stable at ambient pressures. Zurek wonders if some of the materials may be like diamonds. The carbon materials are metastable: They require high pressures to form but they stay stable at low pressures. She thinks it's unlikely that binary materials like the current hydrides will be the answer; she says three-element systems are probably the next frontier.

Like Zurek, Hemley sees close collaboration between experimentalists and theorists driving discovery of stable, high-T_c superconductors. "Conceptually, the process is taking what you learn from new and even exotic materials with these really interesting electronic properties, and then using chemistry to design new materials that might have stability at ambient pressure," he says.

Sam Lemonick is an assistant editor at Chemical & Engineering News, the weekly newsmagazine of the American Chemical Society. A version of this story first appeared in C&EN.

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