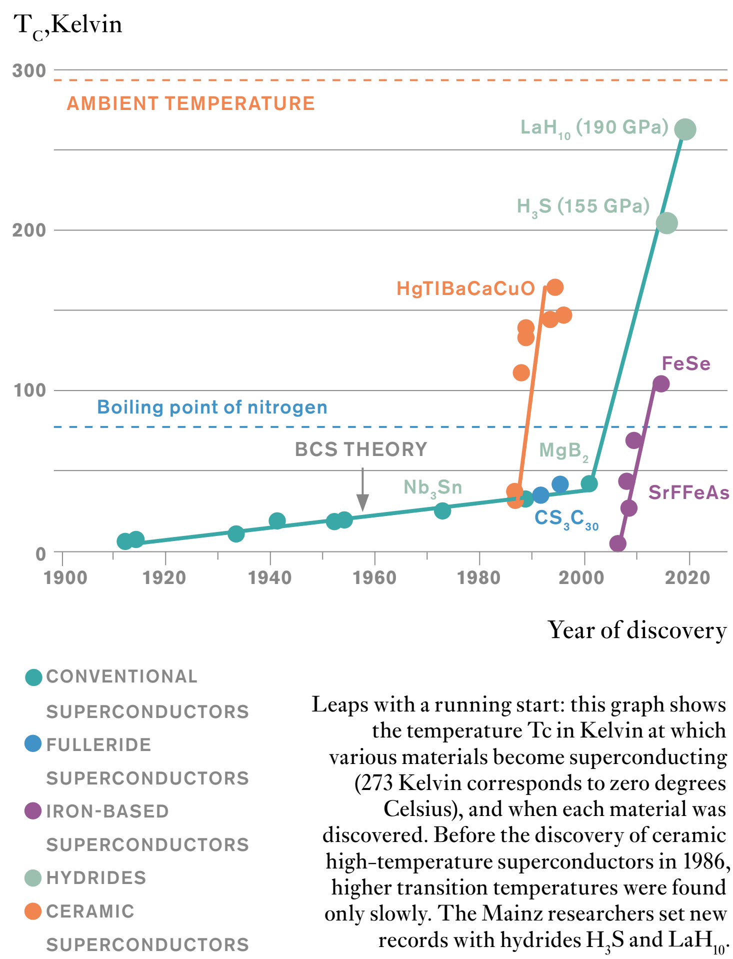
CONDUCTIVE HYDROGEN

TEXT: CHRISTIAN J. MEIER

Materials that can conduct electricity without any losses would improve energy efficiency in many areas. However, superconductivity would have to occur at more practical temperature levels. By taking a new approach, Mikhail Eremets and his team at the Max Planck Institute for Chemistry have come significantly closer to this goal – in particular by placing their materials under truly astronomical pressure.

Gazing around Mikhail Eremets's office, a visitor hardly knows where to look first: physics books share their shelves with metal workpieces, there's a monitor and keyboard on one table and two microscopes stacked on another. There are dumbbells on the floor, and a pull-up bar is mounted above the door. The physicist evidently lives here, in room B 2.75 of the Max Planck Institute for Chemistry in Mainz, and he lives for his research – with success. With his research, Eremets has achieved what few other scientists attain: he has brought an entirely new perspective to a field of research that had long failed to yield the anticipated breakthroughs.

His field of research is the phenomenon of superconductivity – it was discovered over a hundred years ago, was explained 65 years ago, and has the potential to profoundly impact our lives every single day: superconductors conduct electrical current with no resistance. They would enable many new applications: aircraft with light but powerful electric motors, lighter generators for wind turbines, magnetic levitation ("maglev") trains, or an MRI machine in every doctor's office. Superconductors could also pave the way for entirely new technologies: nuclear fusion power plants and ultra-fast quantum computers.



Leaps with a running start: this graph shows the temperature Tc in Kelvin at which various materials become superconducting (273 Kelvin corresponds to zero degrees Celsius), and when each material was discovered. Before the discovery of ceramic high-temperature superconductors in 1986, higher transition temperatures were found only slowly. The Mainz researchers set new records with hydrides H_3S and LaH_{10}.

GRAPHIC: GCO BASED ON A PRESENTATION BY MIKHAIL EREMETS

Slow progress at first

Mikhail Eremets recounts the story of superconductivity as one of the greatest achievements in the field of physics. But it ends on a frustrating note. For now, anyway. The story begins over one hundred years ago with Dutch physicist Heike Kamerlingh Onnes, who was the first to liquefy the noble gas helium – at only four degrees above the temperature of absolute zero. In 1911, he used liquid helium to cool mercury and discovered something: at about minus 269 degrees Celsius, the metal suddenly loses its electrical resistance. Onnes had discovered superconductivity. But a superconductor requiring such extreme cooling was completely unusable for practical applications. And that was how things remained for those materials for a long time. "Progress after that was very slow," Eremets says. Nor did the situation change in 1957, when John Bardeen, Leon Neil Cooper and John Robert Schrieffer used their eponymous "BCS" theory to explain why certain metals conduct electricity without resistance once they are below a specific temperature, known as the critical temperature.

At higher temperatures, electrical resistance occurs because electrons passing through the crystal lattice of a metal continually interact with individual atoms and are deflected from their path. The situation is different in a superconducting material. Here, an electron passing through the lattice draws the positively charged atomic cores in the lattice towards it. Because it takes a finite time for the atoms to spring back into place, a track temporarily forms in which the atoms are closer together than in the rest of the crystal, resulting in a concentration of positive charge. The track thus attracts a second electron, which follows the first at an appropriate distance – because the electrons themselves repel each other. The two electrons now form a Cooper pair, named after one of the fathers of the BCS theory. Many Cooper pairs form in the superconductor.

What happens next can only be understood in the context of quantum mechanics. According to quantum mechanics and the BCS theory, particles can behave like waves. As temperature decreases, the material wave of a particle expands. For the matter waves of Cooper pairs, this means: they are superimposed. Because it is no longer possible to distinguish between individual pairs, they merge to a common state that extends throughout the entire conductor. There are no longer any individual electrons losing energy by rubbing against the atomic lattice. Instead, Cooper pairs form a macroscopic quantum state that is unaffected by occasional obstacles like atomic nuclei. Electrical resistance simply vanishes. "One would think that an explanation of superconductivity would have provided a path for experiments leading to higher critical temperatures," says Eremets. But this hope was initially in vain. One of the most dedicated researchers in this field, the German-American Bernd Matthias, drew a sobering conclusion in 1971: room-temperature superconductivity will forever remain a pipe dream.

Still, physicists have discovered thousands of superconducting materials in the interim. They have even found a second class of superconductors: ceramics with significantly higher critical temperatures of up to minus 135 degrees Celsius, known as high-temperature superconductors. However, this type of superconductivity cannot be explained by the interaction between electrons and the vibrations of the crystal lattice. In contrast, the BCS theory enables more fundamental research into superconductors, and that is what Eremets is working on. In so doing, he is also dispelling a false assumption: the prevailing opinion regarding superconductors was that the critical temperature would always have an upper limit that was still so low that no workable superconductors could ever be found.

So is all hope lost? Mikhail Eremets leans back in his office chair. "Let's take a step back here," he says. He points to a picture showing the planets in the solar system. Jupiter and Saturn dominate with their size. These giant planets are made up mostly of hydrogen. Inside the planets, the molecules are subjected to tremendous pressure due to gravity. The hydrogen becomes more and more compacted as the depth increases. The molecules break up and the hydrogen atoms move very close together. Finally, they form an atomic lattice. Physicists have long suspected that hydrogen becomes electrically conductive in this state and is hence metallic. "Our work mainly involves metallic hydrogen," says Eremets. However, producing it requires a pressure similar to that in the Earth's outer core – roughly three million times atmospheric pressure at ground level. So how do the Mainz researchers plan to generate such high pressure?

Between his thumb and forefinger, Eremets holds a metal cylinder that looks like a pipe fitting. This is a diamond anvil cell that produces tremendous pressures. Pressure works like bicycle gears: it's a question of gear ratios. It's not just how much force is applied that counts: when you concentrate a given force over half the surface area, the pressure that is generated doubles. The anvil cell presses the tips of two diamonds together on

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Fine tuning: Panpan Kong, a scientist in the Mainz team, uses a focused ion beam to process a diamond, visible on the left screen.

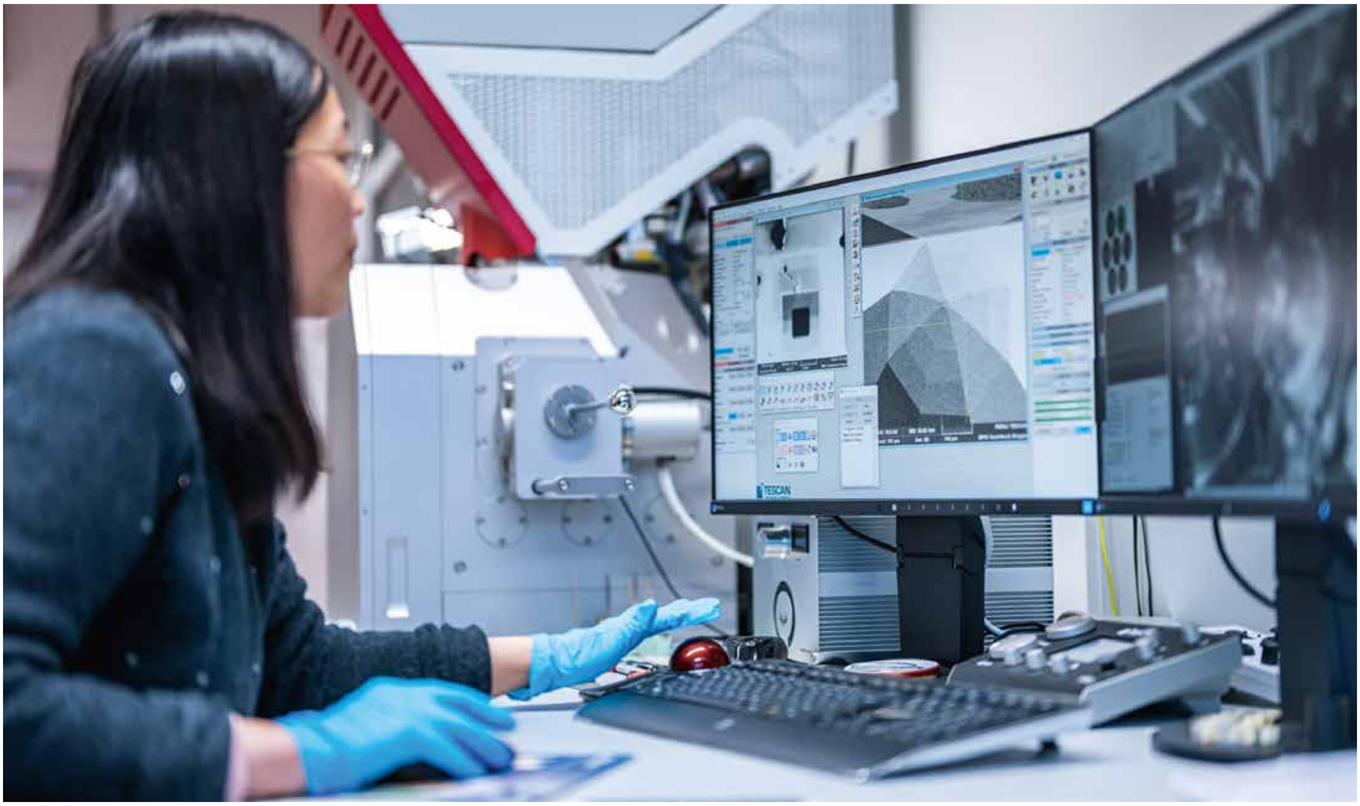

PHOTO: JAN HOSAN

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an area smaller than the cross-section of a hair. So simply tightening the hex socket screws on the cell is sufficient to generate pressures between the diamonds amounting to millions of bars, i.e. megabars, a unit of pressure equal to one million bars. Using this method in 2011, Eremets and his colleague Ivan Troyan succeeded in bringing hydrogen to an electrically conductive state, achieving it at 2.7 million bars of pressure. The pressure at the Earth's surface is roughly 1 bar. The Mainz team and other scientists have since gathered further proof that hydrogen becomes metallic at high pressure.

But what does this have to do with the dream of a room-temperature superconductor? More than 50 years ago, British physicist Neil Ashcroft wrote an article, titled: *Metallic hydrogen: a high-temperature superconductor.* The BCS theory suggests it, argued Ashcroft. "He expressed himself very cautiously," Eremets observes. "At the time, it was simply hard to imagine." However, years later, Ashcroft made another prediction: that chemical compounds that are rich in hydrogen could also have high transition temperatures. According to Ashcroft, the other chemical elements in the compound already exert pressure on the hydrogen, so it takes less additional pressure to make it metallic. At the time, the hope grew that a room-temperature superconductor would now be easier to achieve.

"Then something fascinating happened," says Eremets. Physicists had since learned how to simulate crystals with computers. This was possible due to the rapid growth in the computing power of semiconductor chips. "At the same time, the calculation methods were also being optimized," adds Reinhold Kleiner, who performs research in superconductivity at the University of Tuebingen. "Researchers well know which approximations they can make and which ones they can't." These advancements also made it possible to roughly predict the transition temperature for a superconductor. Physicists made just this calculation for hundreds of hydrogen compounds, including for trihydrogen sulfide (H_3S) – a good choice. Not long after, in 2015, Eremets's team, which included Alexander Drozdov (the first author), caused a sensation: they set a new transition temperature record. Under high pressure, the molecules compressed to form an H_3S crystal. This became superconducting at a balmy minus 70 degrees Celsius. This temperature can be achieved using liquid nitrogen, which is technically much easier to produce than liquid helium. However, the team still had to apply a pressure of roughly one megabar – about a third of that needed to produce metallic hydrogen.

Eremets believes that this success is based on a paradigm shift. Previously, relatively high critical temperatures had been discovered mostly by accident. "Now, theoreticians and experimenters are working together systematically," explains the physicist. For example, his own group has everything they need to conduct experimental studies – from preparation of the samples to their comprehensive investigation. The five-member team in Mainz can thus machine diamonds to a precision of a thousandth of a millimeter. "But our diamonds are useless as jewelry," jokes Eremets: they measure only about two millimeters in size and weigh a mere 0.1 carat. At the tip of these diamonds, the researchers use a complicated focused ion-beam man-sized machine to attach the miniature electrical leads used to study the conductivity of the sample. The contacts come within a few thousandths of a millimeter of each other, but must not touch. The metallic casing of the anvil cell is manufactured by the Max Planck Institute for Chemistry's in-house metal shop.

One of the labs is darkened. That is where the Mainz team uses lasers to heat the sample and to study it spectroscopically. They use what is known as Raman spectroscopy to obtain clues about how the high pressure changes the sample's material properties. The lab also contains a barrel-shaped measuring device known as a SQUID magnometer. This is used to detect a characteristic that only superconductors have: they completely expel magnetic fields from their interior – a phenomenon physicists call the Meissner-Ochsenfeld effect. Superconductors thereby establish a field around themselves that exactly opposes the external magnetic field, enabling a magnet to float above a superconductor. "To perform the measurement within the SQUID magnetometer, we need an especially small anvil cell that can fit inside the instrument," Eremets explains. Before his team obtained the SQUID device, the physicist built a small anvil cell just to indulge his curiosity. He wanted to give it a try to see if it would work. So when the scientific journal Nature required proof of the Meissner-Ochsenfeld effect before publication, Eremets already had the expertise he needed to do just that.

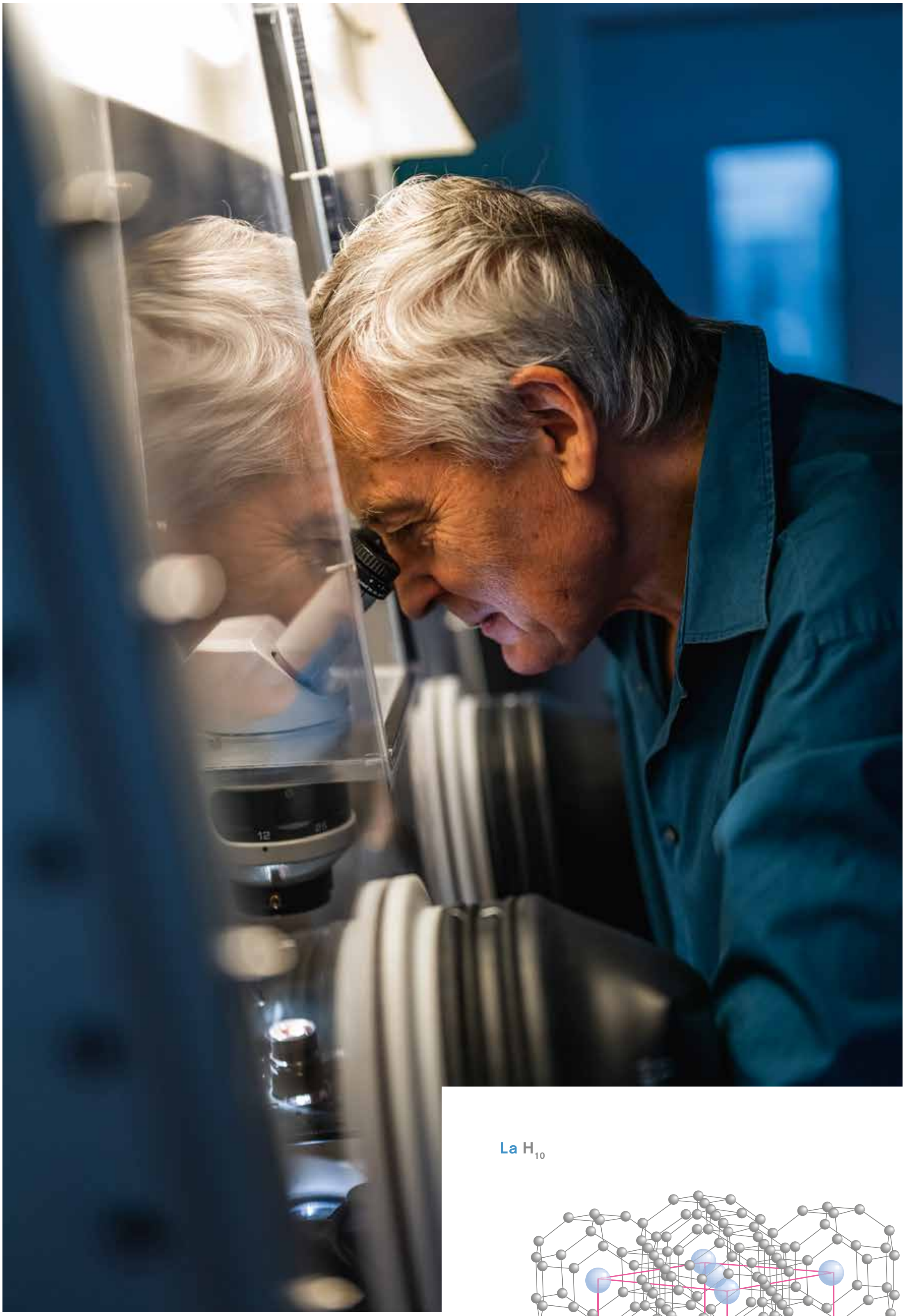
With their instruments, Eremets's team can also address one of the most interesting questions: how can the high transition temperature of H_3S and other hydrogen compounds be explained? Pioneer Neil Ashcroft had already provided the theory for this. According to Ashcroft, hydrogen should be especially well-suited as a superconductor, because it has the lightest atomic nucleus: a single proton. This is especially easily attracted by passing electrons. According to BCS theory, it leaves be-

SUMMARY

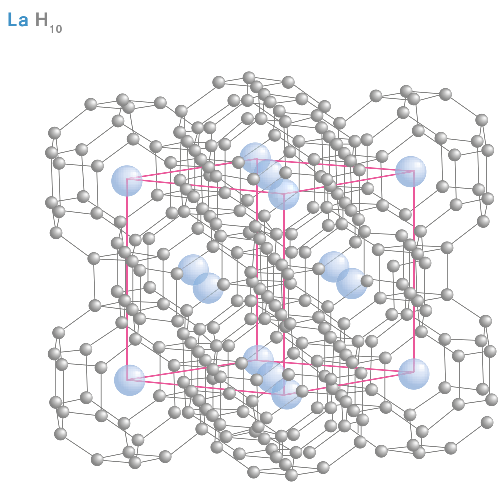
Superconductivity has long been observed only at temperatures far below zero degrees Celsius. A Max Planck team in Mainz has since achieved superconductivity at only minus 23 degrees Celsius.

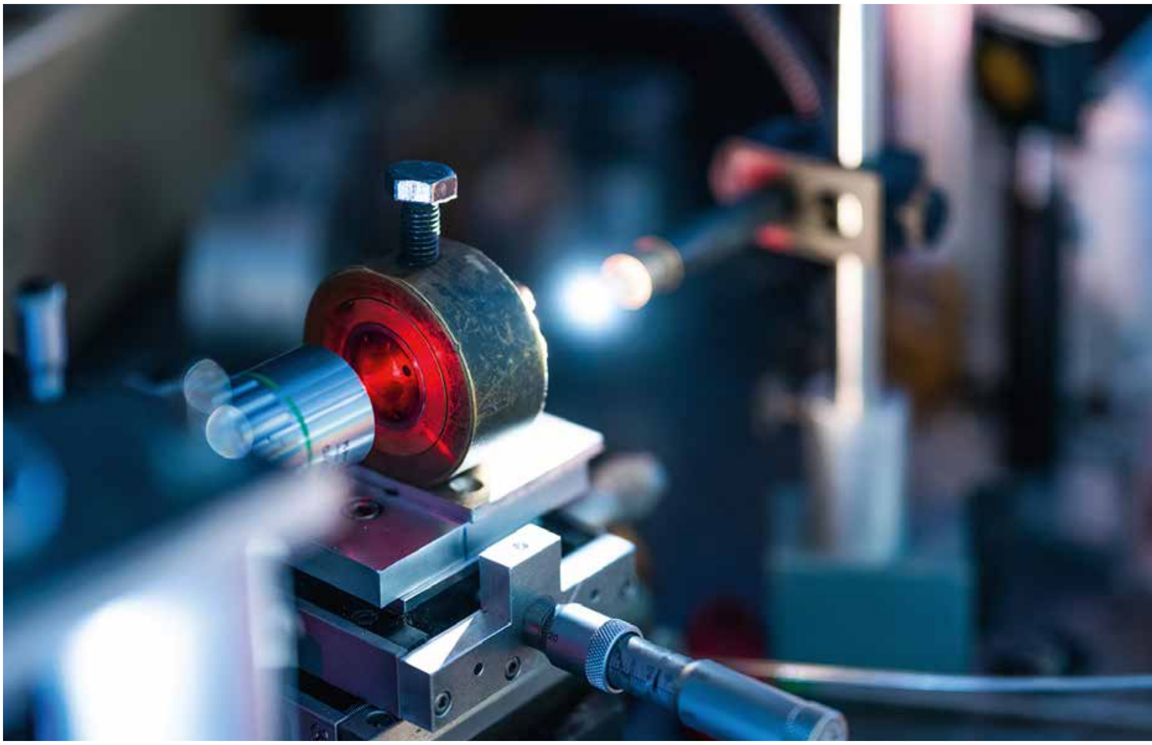
Advances in critical temperature have been made possible because the researchers have been investigating hydrogen-rich materials. However, to date they have had to place these materials under a pressure of more than one million bar.

Hydrogenous compounds that can build up this pressure to a certain degree by virtue of their structure could come closer to superconductivity at practical temperatures and pressures. Another approach is offered by materials whose atoms vibrate at a high frequency, e.g. in metallic hydrogen.



Special atmosphere: Mikhail Eremets uses a glovebox to load a sample into an anvil cell in the absence of air. His team observed a record-high transition temperature of minus 23 degrees in lanthanum hydride (LaH_{10}, bottom right), which consists of many hydrogen atoms (gray) interspersed with lanthanum atoms (blue).





Optical pressure gauge: the researchers in Mainz determine the pressure in a diamond anvil cell by using a laser to measure how the Raman spectrum of the diamonds changes when they are pressed together.

hind a particularly distinct, positively-charged track that can be easily followed by the second electron in the Cooper pair. To test whether this mechanism works in H_3S, the Mainz team repeated the experiment with a heavier hydrogen variant: deuterium. Its atomic nucleus contains one proton and one neutron. Because the mass of the nucleus is now about doubled, it should be more difficult to achieve superconductivity – and the critical temperature should therefore be significantly lower. And that is exactly what the researchers observed: D3S does not become superconducting until minus 120 degrees Celsius.

A new track

This led the Mainz researchers to their next step: if hydrogen is the key, compounds containing an especially high fraction of this element should have the highest critical temperatures. The team selected lanthanum hydride. This substance contains a remarkable ten hydrogen atoms for every atom of lanthanum, a rare earth metal. "It's essentially metallic hydrogen with some lanthanum atoms embedded in it," says Eremets. In 2019, his team set a new record for critical temperature using this compound: it was only 23 degrees below the freezing point of water, a temperature nearly reached on some very cold winter days here in Germany. However, a high pressure of 1.7 megabar was still necessary to achieve it. The journal Nature ranked his work among its ten most important publications of 2019. The following year, researchers at the University of Rochester in New York state presented a critical temperature of 15 degrees Celsius, nearly room temperature, using a compound of hydrogen, sulfur and carbon, upon which they exerted a comparatively high pressure of 2.7 megabar. But Eremets takes a skeptical view of his U.S. colleagues' work: "It's now two years later, and this result still has not been replicated by any other group."

Nonetheless, the research in Rochester points in the right direction: the combination of three elements brings with it the prospect of superconductivity at room temperature or even higher. A team headed by Simone Di Cataldo at the University of Graz has shown this in a model calculation for a compound of boron, lanthanum and hydrogen. In this model, boron and lanthanum form a crystal lattice by themselves, within which metallic hydrogen is interwoven as a second atomic lattice. The first lattice stabilizes the second one, the researchers explain. The model calculation shows the material already losing electrical resistance at 0.5 megabar, although this occurs at a fairly low temperature of about minus 147 degrees Celsius. On the other hand, other model calculations yield an extremely high transition temperature of nearly plus 100 degrees Celsius for a compound of lithium, magnesium and hydrogen, although this occurs at a pressure of 2.5 megabar. However, a combination that yields a low pressure and a high transition temperature has yet to be found. And such a combination probably won't be found any time soon: "It would be misleading to think that this could be achieved through chemical pressure," says Mikhail Eremets. His team therefore wants to understand how superconductivity develops in hydrogen compounds.

PHOTO: JAN HOSAN

This could then yield insights for further studies. “We already know that high vibrational frequencies in the crystal lattice are important,” says Eremets. And this knowledge could be applied in the search for an ideal substance. The researcher also has a possible approach at the ready: diamond contains very rigid chemical bonds between its carbon atoms that vibrate at a similar rate as those in metallic hydrogen. “The problem is that diamond is an electrical insulator,” Eremets explains. In order to function as a superconductor, it would first have to be made to be conductive. “Perhaps we could add small quantities of dopant (or impurity) atoms, to alter its original electrical properties,” suggests Eremets.

Researchers therefore still have a long way to go before they can attain a room-temperature superconductor at normal pressure. Still, Reinhold Kleiner from the University of Tuebingen is cautiously optimistic. “If theoreticians and experimenters can continue working together this effectively, we’ll find superconductivity in other systems as well,” the physicist declares. However, he is skeptical that this will work at normal pressure, and adds: “At this point, I’m just happy with the systematic search that is happening and the results it has yielded.”

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GLOSSARY

BCS THEORY
The explanation for the mechanism of superconductivity in metals, named after John Bardeen, Leon Neil Cooper and John Robert Schrieffer. According to this theory, lattice vibrations promote the formation of Cooper pairs, which form a common quantum state at low temperatures and therefore no longer interact with the atomic lattice.

CRITICAL TEMPERATURE
The temperature below which a material becomes superconducting.

SUPERCONDUCTIVITY
The state in which a material conducts electricity with no electrical resistance.