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Under Pressure

If you're going to try turning hydrogen into a metal, the first thing you will need is a thick skin, says **Michael Brooks**

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WHO would have imagined that the world's greatest wonder material could generate so much heat? Unfortunately, it isn't the useful, thermal kind of heat. Or at least, not yet. After more than 90 years of attempts to create hydrogen in metallic form, the only verifiable output has been friction between those looking for it.

Being the first to produce metallic hydrogen would be a major achievement. So major that multiple groups of researchers have already claimed success. But their rivals are highly sceptical. The response to the latest claim, published in June, is typical. "This paper is much ado about nothing," says Ranga Dias at the University of Rochester in New York. You might think that is harsh, but it is exactly what the authors of the new paper said about his own claim from 2017.

All this aggravation comes from the fact that the stakes are so high. Metallic hydrogen's advocates claim that this version of the common element could revolutionise science and technology. For one thing, it could be a breakthrough rocket fuel, with its conversion back into molecular hydrogen releasing enormous amounts of heat. Then there are the big hopes of planetary scientists: the cores of gas giants like Jupiter are thought to be composed of the stuff. If we could make it in the lab, we might be able to understand how these planets form. Perhaps most enticing of all is metallic hydrogen's rumoured ability to superconduct at room temperature, allowing electricity to flow without energy losses.

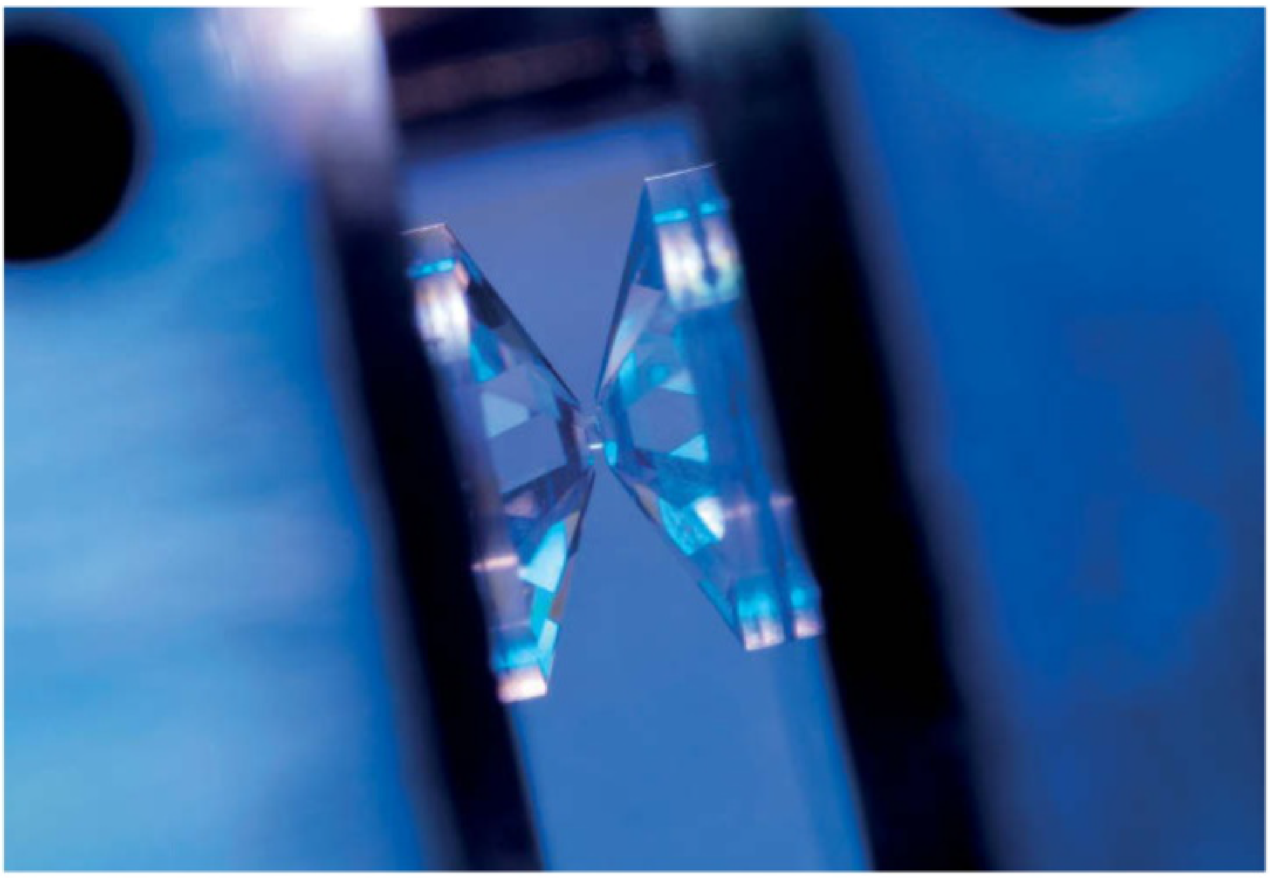
For all these reasons, a successful experiment would be a big deal, says Helen Maynard-Casely at the Australian Centre for Neutron Scattering. "I imagine they all hope they may get a Nobel prize."

The potential seems pretty sweet. So how did things get so bitter?

It all begins with hydrogen, the most abundant element in the universe. It is also the simplest, consisting of a single electron orbiting a proton. That single electron places it in the first column of the periodic table with alkali metals such as lithium, sodium and potassium. These three elements exist on Earth as solids capable of conducting electricity, whereas hydrogen is commonly found as a gas. To turn it into a metal, you would have to get its individual atoms to pack together tightly enough for their electrons to become "delocalised", that is, free to move around the material and thus conduct electricity.

Mounting pressure

The first people to realise that such a transformation might be possible were Eugene Wigner and Hillard Bell Huntington in 1935. They predicted that all hydrogen needed in order to behave like its neighbours in the periodic table was pressure – a lot of pressure. Enabling the electrons of hydrogen's atoms to break loose from their protons and instead roam around the rigid lattice of a solid would take nearly 400 gigapascals (GPa), equivalent to 4 million times atmospheric pressure (or a jumbo jet balanced on a pinhead). Achieving these pressures in the lab is challenging, to say the least. "Getting to pressure in excess of 100 GPa is very much a specialist thing," says Maynard-Casely. "Only a handful of groups are able to do this routinely."



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The first time we got close enough was in 1998. A team of engineers at Cornell University in New York and the University of Maryland squeezed hydrogen samples in what is known as a "diamond anvil". Essentially, this is a pair of diamonds shaped so that their tips are ultra-sharp, about one-quarter of the diameter of a human hair. Although tiny, these tips can trap some hydrogen between them. Then researchers turn a screw to push the two diamonds together and compress the trapped hydrogen. Eventually, after breaking 15 pairs of diamonds, the team managed to crank the pressure between the tips up to 342 GPa, approaching the pressure at Earth's core. According to theory, this should have been about enough to turn the hydrogen metallic. It wasn't.

Four years later, a team led by Paul Loubeyre of the French Atomic Energy Commission (CEA) near Paris showed that this was to be expected. The calculation of the pressure at which metallicity occurs is based on a measure of the "gap" between two very different energy states available to the electron in the hydrogen atom. As the pressure rises, the gap shrinks. This changes the way the electron is able to absorb or emit light. Just before the gap closes and the material becomes metallic, the hydrogen's electrons absorb light, but don't emit it – this causes the material to become increasingly opaque. But once the gap is closed and the electrons are able to exist as free-moving electrical conductors, they will re-emit absorbed light energy, making the material highly reflective. Extrapolating from their observations, Loubeyre and his colleagues reckoned that to create metallic hydrogen you would need pressures of about 450 GPa.

It took another 13 years, but we got there. In fact, we got to 495 GPa, and saw metallic hydrogen. At least, that is what Dias and Isaac Silvera, both then working at Harvard University, claimed in a 2017 peer-reviewed paper in the journal *Science*. Harvard issued a press release in which Silvera called their achievement "the Holy Grail of high-pressure physics".

Not so fast, said Loubeyre. "I don't think the paper is convincing at all," he told the equally famed journal *Nature*. That's because the claim of metallicity is based on a measure of the hydrogen's reflectivity: at 495 GPa it went shiny. But this could have happened for other reasons, says Loubeyre, such as the aluminium oxide coating on the diamond tips altering the hydrogen's reflectivity under pressure.

The pressure attained was also extrapolated from a calibration based on the way that diamond vibrates at high pressures, rather than measured directly. This has failed to convince other researchers, who have suggested the pressure might have been no more than 350 GPa.

Mikhail Eremets at the Max Planck Institute for Chemistry in Mainz, Germany, agrees that the Harvard claim isn't yet proven. In a

Diamond anvils can achieve pressures higher than those at Earth's core

response posted to the arXiv preprint server – a repository of scientific papers that haven't yet undergone peer review – he and his colleague Alexander Drozdov said "we find no convincing evidence for metallic hydrogen in their published data". They know what they are talking about – they, too, are attempting to make metallic hydrogen. As well as citing the possibility that the reflectance change came from the coating on the diamonds, the pressure measurement was "ambiguous", they said. It is obvious what needs to happen now: repeat the experiment. But that is easier said than done because the experiment self-destructed.

Dias and Silvera had always worried that their sample was fragile, which is why they limited the number and range of measurements they carried out. It had been more important, they felt, to publish their landmark results. But when they returned to carry out further investigations, they discovered that the sample was gone. Two years later, they still don't know what happened to it. The sliver of metallic hydrogen – if that's what it was – was just 10 micrometres thick. It might have slipped out of the anvil's jaws and been lost at the bottom of the apparatus. Or it might have just evaporated. But they stand by their claims. "We have answered all of the criticisms," says Silvera. Dias agrees. "We are very confident that we observed metallic hydrogen," he says.

The dispute has left the door open for a definitive sighting of metallic hydrogen – and Paul Loubeyre and his team have slipped in to take the prize. Or they would have done if anyone was willing to hand it over.

In June, Loubeyre posted a bold claim on arXiv. Entitled "Observation of a first order phase transition to metal hydrogen near 425 GPa", the paper was co-authored by Loubeyre's CEA colleague Florent Occelli and Paul Dumas of the French Synchrotron SOLEIL research facility. "Here," it says, "we show a [...] phase transition near 425 GPa from insulator molecular solid hydrogen to metal hydrogen." They were able to achieve this pressure, they say, because of a new kind of diamond anvil that Occelli had helped to develop.

By now, you won't be surprised to learn that the other teams have cried foul. Eremets reckons the observations are interesting, but far from conclusive. Dias is equally dismissive.

> **"It would be a big deal. I imagine they all hope they may get a Nobel prize"**

To prove the existence of a metallic state, it is necessary to demonstrate one of two things, says Dias. The first is that electrical conductivity remains finite as the temperature heads towards absolute zero. The second is to show that the material's reflectance increases with increasing wavelength. "Neither of these were shown," he says.

What's more, he adds, many of the reported observations have been seen before by other groups. Eremets also says that most of these "new" results have been reported before – some of them by his group. He is aggrieved that Loubeyre's preprint doesn't cite any of their work.

More light, less heat

New Scientist's attempts to contact Loubeyre and his colleagues for comment have gone unanswered, as have the questions raised by other researchers. For outside observers like Maynard-Casely, the only way to get definitive answers is to wait for their paper to be published in a peer-reviewed journal. "As a working scientist, I do have to defer to peer review," she says.

So where does this leave us? Will we have to wait another 90 years before we create the ultimate source of rocket fuel and the superconductor found inside Jupiter? Maybe not. Dias and Silvera claim to have repeated their experiment and observed the same result. "About a year ago, we reproduced a shiny sample at high pressure, but for technical reasons we were unable to measure the pressure, so we did not publish," says Silvera. Dias has since moved to the University of Rochester. "I am building a new lab with capabilities to make metallic hydrogen," he says. "I'm confident that we'll be able to replicate this work."

Not that everyone will be waiting with bated breath. It is time to move on, reckons Ashkan Salamat, who studies high-pressure systems at the University of Nevada, Las Vegas. "If we're not careful, we're going to have three or four people who end up just repeating each other's work, and each will claim they are first," he says. That, he adds, would be "a bit boring" when there is so much to explore. "The onset of metallisation seems pretty robust to me. What we don't know is if it's liquid or solid, or whether it could be a room temperature superconductor. There's plenty more to do: what we need now is to work together to answer these questions." ■

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