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Condensed-matter physics

A milestone in the hunt for metallic hydrogen

Serge Desgreniers

An optical study of cold solid hydrogen at extreme pressures indicates that electrons in the material are free to move like those in a metal. This suggests that the long-sought metallic phase of hydrogen might have been realized. **See p.631**

Hydrogen is the most abundant element in the Universe. Its molecular-gas state is simple, but its solid state has proved to be complex. In 1935, it was predicted that solid hydrogen should behave like an electrical conductor at elevated pressures, owing to its molecules being separated into their atomic constituents[1]. This prediction heralded a race to prove experimentally that solid hydrogen displays such metallic behaviour under ultrahigh compression. However, although there have been many claims of proof (for example, refs 2–4), these studies have been challenged. Now, on page 631, Loubeyre *et al.*[5] report that dense hydrogen shows a discontinuous and reversible change in optical reflectivity at extreme pressure and low temperature that can be attributed to a phase transition into a metallic state.

It is common practice to use a device called a diamond anvil cell to achieve ultrahigh compression of a material and to study changes in the material's physical properties at high density. A diamond anvil cell squeezes a sample, which is confined to a microscopic chamber in a thin metal foil, between two diamond anvils (Fig. 1a). The device operates on a deceptively simple physical concept: pressure is inversely proportional to the area of a surface over which a force is applied. In the present case, this simplicity comes with an inherent drawback: reaching extreme pressures inevitably implies working with tiny sample volumes.

Conventional techniques have been the bottleneck in applying extreme pressures to highly compressible materials such as hydrogen. Over the past few decades, research groups around the world have pushed the boundaries of pressure generation. They have also refined the tools and methods needed to accurately estimate pressures applied to a microscopic sample of compressed gas. Nevertheless, debate continues over the accuracy of reported pressures and the interpretation of results drawn from measurements of physical properties.

Recognizing this long-standing problem, Loubeyre and colleagues' research group developed an innovative approach that involves the precise sculpting of diamond-anvil surfaces using a stream of massive ions[6] – a technique called focused ion-beam milling. A similar experimental development has also been reported[7]. The profiled anvils produce extreme pressures that can be reliably estimated, reaching more than 400 gigapascals (about 4 million times Earth's atmospheric pressure). Moreover, the shape of the anvils helps to confine dense hydrogen samples that are suitable for optical measurements.

Under increasingly extreme pressures, dense hydrogen becomes more and more opaque to visible light. For pressures in excess of about 300 GPa, solid hydrogen becomes penetrable only by electromagnetic radiation of lower energy than visible light[2–4,8], such as infrared radiation (Fig. 1b). Loubeyre *et al.* measured the optical transparency of solid hydrogen at pressures much higher than those reached previously, using the near-to-mid-infrared emission from a source of synchrotron radiation – electromagnetic radiation that is produced when charged particles are accelerated in a curved path.

The authors found that a compressed sample of hydrogen blocks all light and exhibits an abrupt increase in optical reflectivity when the pressure is raised above 425 GPa (Fig. 1c). Moreover, they discovered that this transition is reversible. The authors

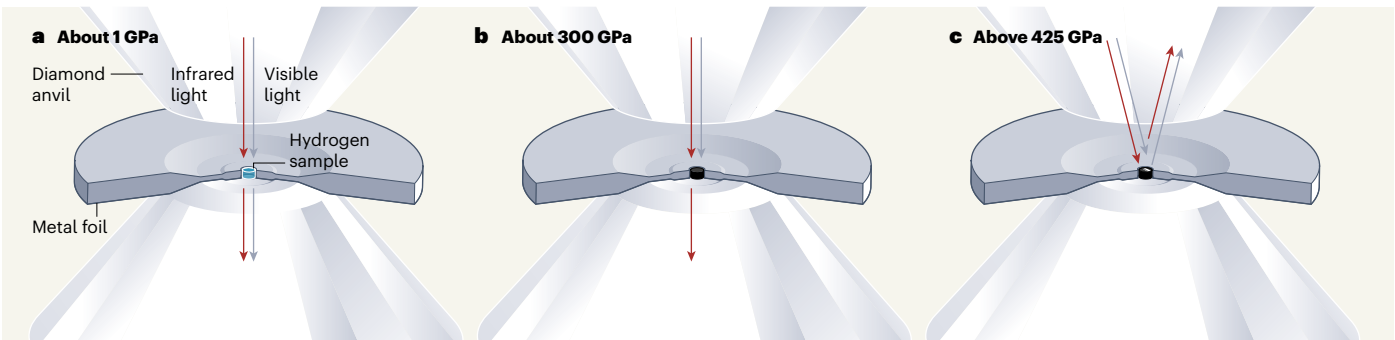

Figure 1 | Effect of increasing pressure on cold solid hydrogen. a, Loubeyre *et al.*[5] have studied solid hydrogen at extreme pressure and low temperature using a device known as a diamond anvil cell. This device compresses a sample of the material, which is confined to a microscopic chamber in a thin metal foil, between two diamond anvils. At first when the pressure is applied, the sample is transparent to both infrared and visible light (GPa, gigapascals). **b**, When the pressure is raised to roughly 300 GPa, the dense hydrogen loses its transparency to visible light. **c**, Finally, when the pressure is above 425 GPa, the sample becomes reflective to both infrared and visible light, indicating a shift into the long-sought metallic state of hydrogen.

attribute the change in optical reflectivity to a pressure-induced phase transition in which electrons in the sample become free to move like those in a metal. Hydrogen remains as a molecular solid up to the transition pressure; it possibly stays in this state above 425 GPa, but it is difficult to confirm this by spectroscopy because there is a reduced coupling between light and matter in these extreme conditions.

It can certainly be argued that a definite proof for metallic hydrogen would come only from a measurement of the sample's electrical conductivity at high pressure as a function of temperature. Solid hydrogen should exhibit a high level of electrical conduction that should then decrease as the sample temperature is raised. However, even with experimental techniques developed in the past few decades to study condensed matter in extreme conditions, electrical-transport measurements of hydrogen remain a huge challenge[9,10].

Nevertheless, Loubeyre and co-workers' findings should be considered as a close-to-definite proof of dense hydrogen reaching a metallic state in extreme-pressure conditions. Computational predictions of the pressure at which molecular hydrogen enters a metallic state still lack accuracy, because they require many different quantum-mechanical corrections that are difficult to address. However, the experimental value of 425 GPa agrees with calculations[11] that predict a transition in hydrogen to a different solid phase at a similar pressure.

Loubeyre and colleagues' study has combined innovative techniques for ultrahigh-pressure generation with advanced experimental methods using synchrotron radiation. In doing so, it has raised expectations for the discovery of other remarkable properties of solid hydrogen at extreme density. For the time being, many questions remain. For instance, could electrical resistivity be measured across the metallic transition? Could superconductivity at a record-high temperature be achieved in hydrogen? And could the molecular order be disrupted under ultrahigh pressure and lead to an atomic phase in the solid state?

Competition is still strong between different research groups seeking to answer these questions, and to further unveil and understand the characteristics of hydrogen at extreme density. More exciting findings are sure to come at every stage of the race.

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Computational biology

Protein-structure prediction gets real

Mohammed AlQuraishi

Two threads of research in the quest for methods that predict the 3D structures of proteins from their amino-acid sequences have become fully intertwined. The result is a leap forward in the accuracy of predictions. **See p.706**

Proteins perform or catalyse nearly all chemical and mechanical processes in cells. Synthesized as linear chains of amino-acid residues, most proteins spontaneously fold into one or a small number of favoured three-dimensional structures. The sequence of amino acids specifies a protein's structure and range of motion, which in turn determine its function. Over decades, structural biologists have experimentally determined thousands of protein structures, but the difficulty of these studies has made the promise of a computational approach for predicting protein structure from sequence alluring. On page 706, Senior *et al.*[1] describe an algorithm, AlphaFold, that takes a leap forward in solving this classic problem by bringing to bear modern machine-learning techniques.

The diversity of protein structures precludes the possibility of obtaining simple folding rules, making structure prediction difficult. Protein folding is ultimately driven by quantum mechanics. Were it possible to compute the exact energy of protein molecules from quantum theory, and to do so for every possible conformation, then predicting a protein's most energetically favoured structure would be easy. Unfortunately, a quantum treatment of proteins is computationally intractable (quantum computers might change this), and the total set of possible conformations that any protein can take is astronomical, prohibiting such a brute-force approach.

This has not stopped scientists from attempting a direct attack on the problem. Physical chemists have devised tractable, but approximate, energy models for proteins[2], and computer scientists have developed ways to explore protein conformations[3]. Much progress has been made on the first problem but the second has proved more recalcitrant.

The set of shapes that a protein might take can be likened to a landscape: different locations in the landscape correspond to different shapes, with nearby locations having similar shapes. The height of a location corresponds to how energetically favourable the associated shape is, with the lowest point being the most favoured. Natural proteins evolved to have funnel-shaped landscapes that enable newly synthesized proteins, jostled by the thermal fluctuations of the cell, to cross the landscape and find their way to a favoured conformation in physiologically relevant timescales (milliseconds to minutes)[4]. Algorithms can search the landscape to find favoured conformations by following the landscape's inclination, but the ruggedness of the terrain causes them to get stuck in troughs and valleys far from the lowest basin.

"The algorithm outperformed all entrants at the most recent blind assessment of methods used to predict protein structures."

The course of the structure-prediction field changed nearly a decade ago with the publication of a series of seminal papers[5–7] exploring the idea that the evolutionary record contains clues about how proteins fold. The idea is predicated on the following premise: if two amino-acid residues in a protein are close together in 3D space, then a mutation that replaces one of them with a different residue (for example, large for small) will probably induce, at a later time, a mutation that alters