HIGH PRESSURE

Compressed hydrogen heats up

The finding of a new molecular phase in hydrogen under high pressure and moderate temperature adds to the complexity of its phase diagram.

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Hydrogen is by far the most abundant element in the Universe and constitutes the major chemical component of stars. Scientific studies of hydrogen at extreme pressures and temperatures — simulating those that it experiences inside stellar bodies and gas giants — are crucial for understanding the rich variety of unusual states and structures, and strange properties, that dense hydrogen demonstrates. But the combination of high pressures with moderate temperatures (>200 GPa and 550–1,300 K) has long been an experimentally inaccessible 'no man's land' for hydrogen, and its behaviour in this regime has been a challenge to explore (Fig. 1). Writing in *Nature Materials*, Howie *et al.* report[1] how they have now overcome this difficulty by coupling hydrogen confined in a diamond-anvil cell with resistive heating, allowing them to observe a new, dense form of hydrogen with unusual optical properties.

As the first element in the periodic table, hydrogen consists of only an electron and a proton, and therefore has the simplest subatomic structure of all the elements. The study of the hydrogen emission and absorption spectrum a century ago by Rutherford and Bohr revealed the nature of atomic orbitals, a finding that arguably led to the emergence of modern physics. Likewise, the study of dense hydrogen has spearheaded exploration into the high-pressure domain. Interestingly, despite its simple single-proton structure, high-pressure studies of hydrogen have unveiled a wealth of unusual structures and properties. For example, under compression, molecular hydrogen gas solidifies and is predicted by theory to transform into a number of exotic, dense states that are anything but simple. These include a low-temperature, alkali-metal-like atomic crystal[2], a very-high-temperature superconductor[3], a new type of ordered quantum fluid ranging from superconductors to superfluids[4], and a low-temperature molecular quantum fluid[5]. Although these are yet to be experimentally proven, their fascinating nature, and suggestive novel physics, have fuelled efforts in experimental advances to reach ever higher pressures and more challenging sample characterization. In turn, new experimental findings constrain, develop and stimulate new theories.

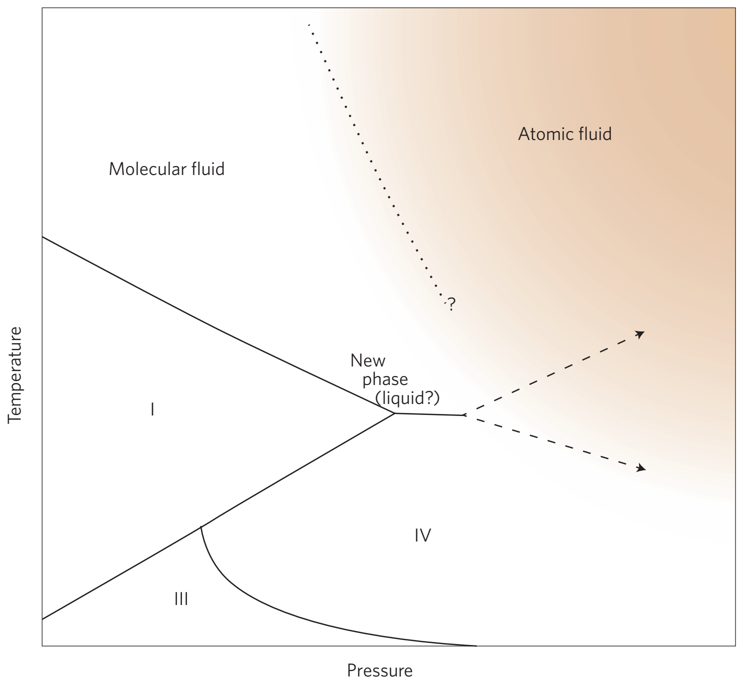

Figure 1 | Schematic of the phase diagram for hydrogen at high pressures (~200–300 GPa) and moderate temperatures (~200–700 K), based on data from ref. 1. The properties of the newly discovered molecular phase, and the question of what happens in the region at higher pressures and temperatures (shown as shaded area), represent exciting areas for future research. Some possible extensions of the phase boundaries are shown by dashed arrows. The dotted line indicates a possible boundary between the molecular and atomic fluids.

Recent technological advances in static and dynamic experimental compression capabilities have enabled studies of hydrogen under extreme compression and variable temperature, leading to the discovery of a number of phase transformations. Dynamic shock-wave experiments[6] have revealed the transformation from an insulating hydrogen liquid to a conducting fluid above 140 GPa and thousands of kelvin. Static experiments using diamond-anvil cells have extended the maximum pressure at which hydrogen has been studied to beyond 300 GPa at cryogenic temperatures, where no fewer than five solid phases have been found[7,8]. With its strong quantum effect and extremely high compressibility, the rich physics of hydrogen suggests that other unusual phenomena may occur[9]. A missing piece of the puzzle, however, has been what happens at very high pressure and moderate temperature. This is the key region near the boundary between the fluid and solid state, where new phases and interesting properties are expected, and it has been inaccessible in dynamic studies because of rapid temperature rises during compression. It is also challenging to probe this boundary in static experiments, owing to technical difficulties in containing hot hydrogen above room temperature. Howie and co-workers have met this challenge by improving the resistively heated diamond-anvil cell technique[10] and hydrogen-containment method, enabling them to reach 570 K at 245 GPa in pure hydrogen. In this region, they observed a striking change in the optical Raman vibrational spectra, indicating the discovery of a new molecular phase (Fig. 1). If this phase is indeed the long sought-after molten hydrogen[5], as interpreted by the authors, this will be the coldest melt for all known materials above 200 GPa. To put this in context, compression usually causes a liquid to freeze into a solid; in very rare cases, such as ice and water, compression causes a solid to melt. Hydrogen would set a record high pressure and record low temperature for pressure-induced melting.

This discovery of a new hydrogen phase represents a significant step forward. It is likely to stimulate the development of key experimental tools and techniques to answer the number of questions its observation raises. For example, is the new phase indeed a liquid? Or is it one of the exotic solids predicted by theory, such as the alternating layers of disordered H_2 and graphene-like $3H_2$ rings[11]? Is the melt conductive? Extension of experimental probes into this region, such as infrared spectroscopy, electrical conductivity measurements and X-ray diffraction, in addition to Raman spectroscopy, will be necessary for providing definitive answers to some of these questions. ❐

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