PHYSICS

Under Pressure, Deuterium Gets Into Quite a State

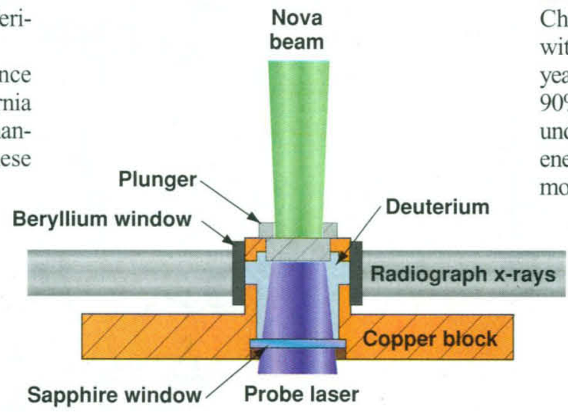
In experiments mimicking conditions inside giant planets, deuterium is more compressible and becomes metal-like at lower pressures than expected

To hear Gilbert Collins describe it, conducting experiments with the world's most powerful laser is a bit like working in a war zone: It demands long nights of attention punctuated by loud explosions. Collins and colleagues place a drop of deuterium into a penny-sized copper container, align an array of equipment around it, then retreat to a remote control room. After a short countdown, the Nova laser fires with a deafening crash. One of its 10 beams, momentarily carrying more power than the output of all the electrical generators in the United States, pulverizes the deuterium with a flash of green light. Having recorded the event, the team cleans up the mess, sticks the resulting bent copper on the shelf for posterity, and sets up for another shot.

Collins and his colleagues at Lawrence Livermore National Laboratory in California are generating more than a museum of mangled metal, of course. The data from these pioneering experiments (reported on page 1178) show how deuterium and hydrogen behave in the hot, pressurized interiors of giant planets. That information could help resolve a number of mysteries, such as why Saturn appears to be so much younger than the rest of the planets in the solar system, says Gilles Chabrier, a physicist at the Ecole Normale Supérieure in Lyon. The work is "tremendously important for astrophysics," he says, and may help answer basic questions about condensed matter. "No one knows what happens at these high pressures and temperatures," he says. Adds Russel Hemley, a physicist at the Carnegie Institution of Washington: It gives a glimpse of "a different domain of matter."

Matter is well understood under earthly conditions. Physicists know at what combinations of temperature and pressure water boils or freezes, for instance. And, by compressing materials with diamond anvils or explosive gas guns, they've mapped out the "equations of state" for many materials that describe how they behave under high pressure. But neither anvils nor gas guns are yet capable of simulating the high temperatures and pressures at the core of large planets. And at even higher pressures, truly exotic states of matter are expected to form. At some point, even diamond, the most durable insulator, is predicted to break down and conduct like a metal.

The Livermore group figured it could recreate some of those conditions with the Nova laser, which was built to compress fuel pellets for fusion research. To watch what happens to deuterium, the Livermore physicists place a sample in a small copper cell outfitted with a plunger at one end and thin beryllium windows on the sides. When the laser hits the plunger, it sends a shock wave through the deuterium. By shining a beam of x-rays through the two windows, the team can track the shock speed and infer the pressure and resulting density of the deuterium over the 5 or 10 billionths of a second before the whole assembly flies apart. And by using a laser to measure the reflectivity of the deuterium through another window, they can tell when it makes the jump to a conducting (and hence reflecting) metallic fluid. "This is a monumental experiment," says William Nellis, a physicist at Livermore who works with gas guns, "I take my hat off to them."



Big squeeze. A shock from the Nova laser makes a drop of deuterium feel like it is at the core of Saturn.

SOURCE: LAWRENCE LIVERMORE NATIONAL LABORATORY

Some of the results are surprising. The group found, for instance, that the deuterium compressed easily—its density increased sixfold at pressures of about a half a megabar, instead of reaching a factor of four compression predicted by traditional models. That could be a rare bit of good luck for the laser fusion program, which aims to squeeze deuterium and tritium fuel pellets to maximum density to trigger fusion. But it's a puzzle for theorists. "It turns out a lot of their data disagrees with every [theoretical model]" available, says David Ceperley, a theorist at the University of Illinois, Urbana-Champaign.

Some models predict that at some high temperature and pressure, deuterium should undergo an abrupt phase transition. In this picture, the pressure frees one electron to wander from its atom, which induces others to follow, dissolving the structure. This soup would be hard to compress since the shock would heat it and cause it to expand. But Ceperley suspects that at the temperatures reached in the Livermore tests, the soup may be a little more complicated. In his computer simulations, which laboriously model every proton and electron, Ceperley has found that hydrogen or deuterium atoms can sometimes link up into chains bound by borrowed electrons. If such structures do form, he conjectures, they might absorb some of the energy of the shock without heating the fluid or causing it to expand.

As a practical matter, says Chabrier, the data give physicists their first real look at what conditions may be like inside giant planets such as Saturn. Equations of state suggest that, given Saturn's relative warmth, it has only existed for about 2 billion years. "Which is crazy," Chabrier says, since it should have formed with the rest of the solar system, 4.5 billion years ago. If hydrogen, which makes up over 90% of Saturn, goes soft at high pressures or undergoes a phase transition, it could store up energy in the same way that water vapor has more energy than liquid water. This stored energy might keep Saturn relatively warm in its old age.

The Livermore group also found that deuterium conducts like a metal at lower pressures than many models had predicted. That could help explain the strong magnetic field of planets such as Jupiter whose massive size creates a high-pressure environment. "So far, we have no clear explanation for the magnetic fields in [these] planets," Chabrier says.

Several other groups are planning similar high-pressure work with the Phebus laser in France and possibly the Gekko laser in Japan. And deuterium won't be the only element getting the squeeze. Michel Koenig at the Ecole Polytechnique in Palaiseau, France, says he and colleagues hope to work with the Livermore group to laser-shock iron and water, which may form a good part of large planetary cores. The Livermore group has recently put the screws to diamond. Already, they say, they've seen signs that it may turn into a metallic liquid under the strain. "It's the hardest known material," says Richard Martin, a theorist at the University of Illinois, Urbana-Champaign, who has theorized about how diamond might be transformed by high pressure. "I'd be really interested to see where it breaks down."

–DAVID KESTENBAUM