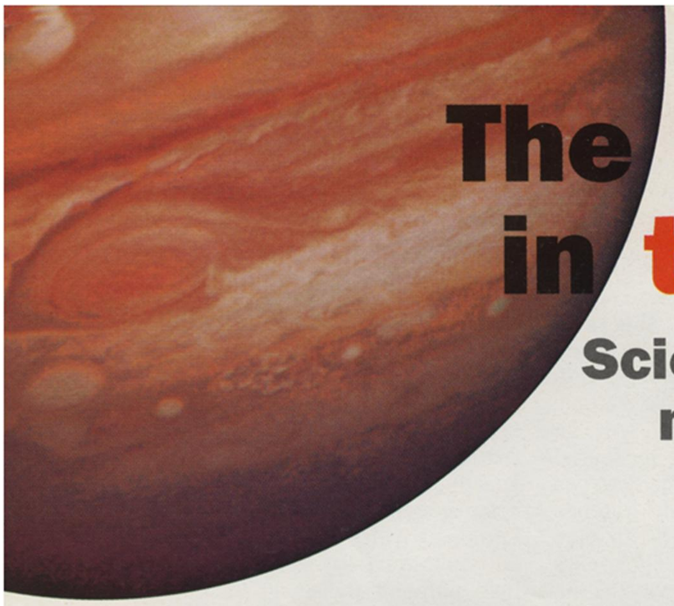


The Lightest Metal in the Universe

Scientists make a fleeting metal from hydrogen

By RICHARD LIPKIN

A physicist's fantasy, an alchemist's dream. Blasting a metal piston at 16,000 miles per hour into a tiny droplet of liquid hydrogen, researchers recently witnessed for the first time the change of that element, ordinarily a wispy gas, into a metal that conducts electricity.

The action took place in a mere millionth of a second in a tiny chamber at the end of a 60-foot-long gun at the Lawrence Livermore (Calif.) National Laboratory. The proceedings began with a detonation that hurled a speeding, dime-shaped projectile into a dab of liquid hydrogen only half a millimeter thick.

That impact and its reverberations, which compressed the volatile element to nearly 2 million atmospheres of pressure and cooked it to 4,400 kelvins, lasted long enough for researchers to watch hydrogen's electrical resistivity drop to a value typical of metals such as cesium and rubidium at that temperature.

"Scientists have been after this result since the early part of the century," says William J. Nellis, a physicist at Livermore. "Metallic hydrogen has been one of the Holy Grails of condensed matter physics ever since its existence was first predicted in 1935." With fellow physicists Samuel T. Weir and Arthur C. Mitchell, Nellis described the experiment during the March meeting of the American Physical Society in St. Louis, as well as in the March 11 Physical Review Letters.

Although hydrogen is the simplest element, composed of one proton and one electron, and accounts for 90 percent of the matter in the visible universe, it has proved far more complicated than any theorist had predicted. Turning the highly reactive, explosive gas into a metal defied experimenters for more than half a century, as they cooked, cooled, and compressed hydrogen using a variety of different experimental apparatuses.

Despite their success at squeezing hydrogen into a liquid and eventually into a crystalline solid, scientists have until now found themselves hamstrung in their attempts to turn hydrogen into a metal. As gas or liquid, hydrogen atoms stay paired; in a crystal, the atoms glide into an ordered lattice. To form a liquid metal, however, the atoms must share their electrons, which then roam free among protons, giving rise to electrical conductivity.

Although experiments at room temperature in small containment chambers made of diamond, called diamond-anvil cells, brought hydrogen stably to pressures exceeding 2 million atmospheres, evidence of electrical conductivity never turned up—leaving scientists both frustrated and perplexed.

In the latest experiment, Nellis' group used a two-stage gun to send multiple shock waves through a small hydrogen sample held in a sapphire anvil, squeezing the chilled liquid to one-ninth its original volume. The temperature soared, fluctuating between 2,200 and 4,400 kelvins.

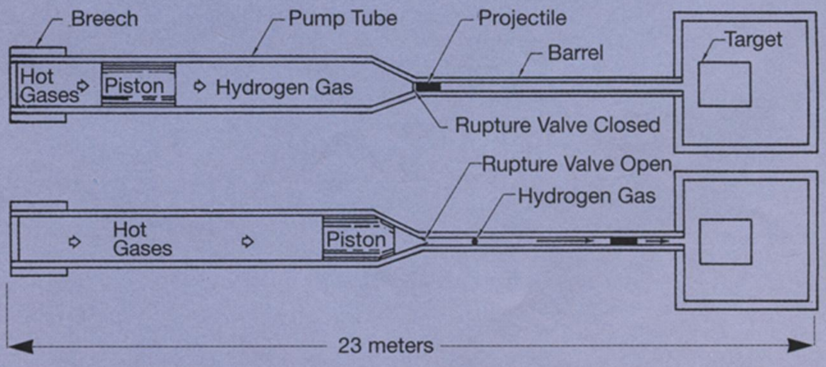
In fact, by pummeling the hydrogen with multiple shock waves rather than one mighty blow, they managed to keep the temperature to only one-tenth of what it would have been otherwise. The process created pressures between 0.9 and 1.8 million atmospheres, leading to a transition of hydrogen to a liquid metal at roughly 1.4 million atmospheres.

Because of hydrogen's explosiveness, "this is a tricky experiment to pull off," says Nellis. "When we fire the gun, no one's allowed to be in the room." Indeed, the gun wields the explosive force of 5 pounds of dynamite.

"Fortunately, we've had practice doing this," says Nellis.

"This latest experiment marks an interesting point along the road to a deeper understanding of hydrogen," says Neil Ashcroft, a physicist at Cornell University. "If you look at the distribution of matter in the visible universe, you find that most of it exists as hydrogen in hot, dense, liquid form," which constitutes most stars.

"So in order to explain the nature of the



Researchers used a two-stage gun to squeeze hydrogen gas, making a metal. First (top), exploding gunpowder drives a piston forward, pressurizing hydrogen gas into a pump tube. Second (bottom), the pressurized gas ruptures a valve, firing a projectile down a long barrel into a target vessel; there, the hydrogen compresses, becoming a metal.

Diagrams: Nellis *et al.*/Lawrence Livermore Natl. Lab.

universe," Ashcroft adds, "this experiment must be seen as an important one."

As far back as 1926, physicist Ralph Fowler at Cambridge University in England speculated that at sufficiently high temperatures and pressures, molecular hydrogen would transform into a dense plasma, or ionized gas. In 1935, physicists Eugene Wigner and Hillard Huntington at Princeton University proposed that, at high pressure but lower temperature, hydrogen molecules would break up and re-form as a lattice of single atoms that could conduct electricity.

Then, in 1968, Ashcroft suggested that if metallic hydrogen could be stably produced, it might behave as a superconductor. As recently as last July, Ashcroft wrote in Physics Today that "60 years after Wigner's original prediction, physicists are still waiting for conclusive proof that hydrogen can be made to conduct, never mind superconduct, electricity."

Now, he hastens to add, "Nellis' group has done exactly this. They've put probes into the hydrogen sample, clearly showing that the dense liquid has shifted into an electrically conductive form."

"These results really are exciting," says Russell J. Hemley, a physicist at the Carnegie Institution of Washington, D.C. "They confirm to us the surprisingly rich physics of hydrogen at high pressures."

Hemley, who along with Carnegie geophysicist Ho Kwang Mao specializes in pressurizing hydrogen in diamond cells, says that "these results are important to us because, in the same range of pressures, we've found many unusual phenomena in hydrogen in its solid, crystalline form."

By squeezing and cooling hydrogen slowly, in contrast to Nellis' explosive shock wave methods, Mao and Hemley have succeeded in using X-ray diffraction and infrared spectroscopy to peer inside the diamond cells and show hydrogen's transitions from a gas to a liquid to a crystal.

Yet owing to hydrogen's volatility under those conditions, the Carnegie group hasn't been able to measure the compressed hydrogen's conductivity directly—hydrogen reacts explosively with metal sensors. This twist has stymied their efforts to confirm or disprove hydrogen's current-carrying capacity.

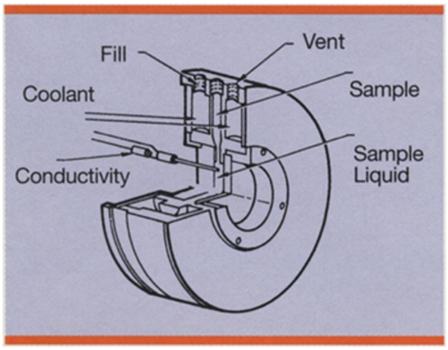
At pressures above 1.5 million atmospheres, hydrogen shows "evidence of charge transfer and changes in the material's electronic structure," says Hemley. Rather than fully conducting current, like a metal, the pressurized hydrogen transfers charges inefficiently, more like a semiconductor. Hemley and Mao described this ionic hydrogen in the March 4 Physical Review Letters.

Hemley and Mao keep hydrogen cold in the diamond cells not only to limit its volatility but also to remove complications introduced by high temperature. "We're interested in hydrogen's fundamental quantum mechanical properties," Mao says.

He adds that he's astonished at the speed with which research groups are now accumulating information about dense hydrogen.

"Five years ago, we didn't even think it would be possible to measure the crystal structure or infrared spectra of hydrogen at 1 million atmospheres of pressure," he says. "But now they've both been done."

While the fleeting observation of metallic hydrogen has no immediate practical implications, it has done much to buttress existing atomic theories and to open new questions. Mao wonders, for example, whether metallized hydrogen could be "quenched" by slowly relieving the pressure, leaving a metal stable under room temperature and pressure—somewhat in the way that elemental carbon re-forms into diamond.



A cross section of the gun's target, in which hydrogen forms a metal.

Hydrogen's abundant nature, energy, and volatility make it a potentially rich source of fuel. During combustion with oxygen, for example, it spews large amounts of energy while leaving only a puddle of water. Although most researchers view pure hydrogen metal as a highly impractical fuel, they still ponder whether some other element could be added to stabilize a hydrogen-rich solid for use as, say, a rocket fuel or industrial explosive, says Mao.

"We've found a variety of hydrogen-rich compounds that remain stable under moderate pressures [about 30,000 atmospheres]," says Hemley. He and Mao reported in the March 8 Science the creation of a high-pressure compound of hydrogen and methane. "One can think about stabilizing [such mixtures] so that they can exist under normal conditions."

"This isn't exactly storing metallic hydrogen," Hemley adds. "But it would be storing hydrogen within compounds, which might eventually be used as fuels."

Perhaps the greatest short-term impact of detecting metallic hydrogen will show up in revised models of the structures of gaseous planets, primarily Jupiter and Saturn, and the planets recently seen circling distant stars.

Densely packed with hydrogen and helium, Jupiter and Saturn contain 300 to 400 times the mass of Earth. Together, the two planets account for more than 90 percent of the mass in the solar system, discounting the sun, says Ashcroft. "Over half of it is now thought to be in metallic form. That means that the most abundant substance in our planetary system is metallic hydrogen."

"That means we should try to understand it," he observes. "Shouldn't we?"

Nellis notes that "the pressures and temperatures we're using to measure hydrogen's conductivity may be representative of those on Jupiter." Because experiments have now shown that hydrogen metallizes at lower pressures and higher temperatures than previously thought, scientists are changing their views of the Jovian core and surface to try to account for Jupiter's large magnetic field, which averages more than 12 times that of Earth.

"A planet's magnetic field depends on the ability of its core to conduct current," says Ashcroft. "If the conductive portion of that planet is larger than expected, then we must alter our view of how the planet generates its magnetic field."

"Our results suggest that metallic liquid hydrogen in Jupiter's interior extends out farther than has been assumed," Nellis says. Moreover, the convective patterns created by a swirling sea of conductive hydrogen "probably explain Jupiter's enormous magnetic field."

Jupiter's magnetic field causes the planet to radiate electromagnetic energy at three times the rate it receives energy from the sun. The new data on metallic hydrogen may help to account for this extra energy.

"This has strong implications for planetary science and astrophysics," Ashcroft says.

"These results will alter our view of Jupiter," adds David J. Stevenson, a planetary scientist at the California Institute of Technology in Pasadena.

The new data may require a rethinking of how Jupiter's interior is structured, as well as of the differences between Saturn and Jupiter, Stevenson says. Moreover, the data support a model suggesting that helium may condense out of Jupiter's atmosphere, he adds.

"Owing to these findings, some people may have to rebuild their models of Jupiter from scratch," says Edwin E. Salpeter, an astrophysicist at Cornell. He speculates that, ironically, the new data may prompt a return to models of Jupiter's core common a decade ago. In these older pictures Jupiter had more liquid metallic hydrogen in its core.

Yet unlike 10 years ago, planetary scientists can now work with experimental data, not just theoretical estimates. "Then, it was all guesswork," says Salpeter. "Now, it's the real thing." ☐