# Liquid deuterium pressured into becoming metallic

**The world's strongest pulsed-power source takes a shot at an 80-year-old condensed-matter-physics problem.**

Hydrogen is the simplest and most abundant element in the universe. But that simplicity belies its often unpredictable nature. A case in point: Unlike the alkali metals that sit below it on the periodic table, hydrogen, even in its solid phase, remains a molecular insulator down to the lowest temperatures.

In 1935 Eugene Wigner and Hillard Huntington predicted that squeezing solid hydrogen to a sufficiently high pressure could cause it to shed its molecular bonds and transform into an atomic metal. The race to find the insulator-to-metal transition in hydrogen was on, but it's turned out to be a marathon rather than a sprint.

High-pressure experiments are notoriously difficult, and ones on hydrogen even more so. Diamond-anvil cells, the go-to equipment for static-compression experiments, are hampered by hydrogen's tendency to penetrate into the diamond and cause cracks. Dynamic experiments using shock compression reach higher pressures, but they heat the sample to high temperatures and only access specific values of pressure and temperature that depend on the system's initial state. Still, experimentalists have subjected hydrogen to pressures of 320 GPa using static techniques and 500 GPa using dynamic methods but have not found the metallic phase.

Now Marcus Knudson and Mike Desjarlais of Sandia National Laboratories and their colleagues at Sandia and the University of Rostock in Germany think they have sighted the elusive transition. The group used Sandia's Z machine to dynamically compress liquid deuterium[1] to pressures greater than 300 GPa at temperatures between 1000 K and 2000 K. Their measurements indicate that the liquid abruptly goes from being an insulator to being a metal at about 300 GPa.

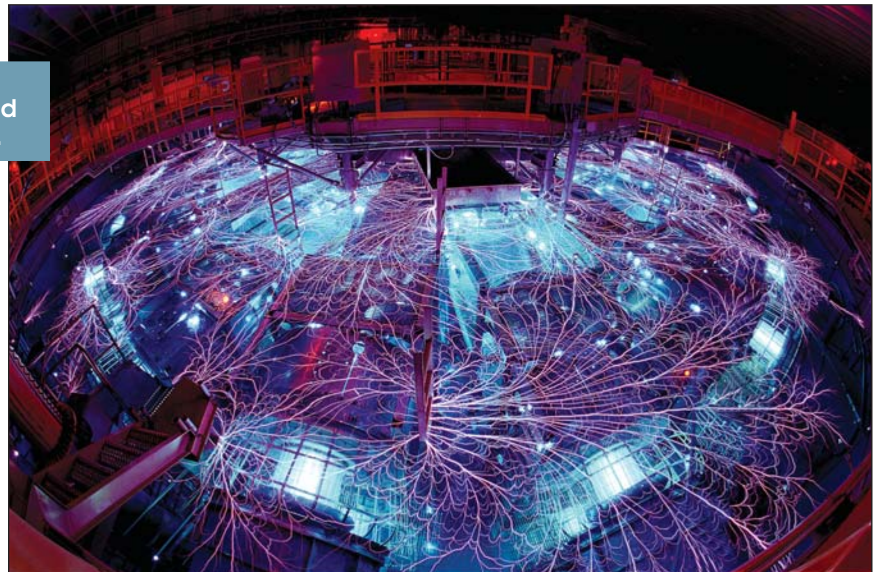

**Figure 1. To squeeze liquid deuterium** into its metallic phase, researchers discharged the 2160 capacitors of Sandia National Laboratories' Z machine and sent a precisely shaped 1-µs current pulse that delivered 2 MJ of energy to a target at the machine's center. The power transmission cables, as big around as small cars, are submerged in oil or deionized water, which serves as an insulator. Electrical arcs that play over the device during discharge, shown here, make for a dazzling display. (Photo by Randy Montoya/Sandia National Laboratories.)

## A shocking squeeze

The world's most powerful pulsed-power generator, the Z machine, shown in figure 1, is best known for inertial confinement fusion and weapons-related research. But under Sandia's Z Fundamental Science Program, it also serves as a powerful tool to study the properties of materials at extreme temperatures and pressures. (See PHYSICS TODAY, June 2014, page 24, and the article by Paul Drake, June 2010, page 28.) For their experiment, Knudson, Desjarlais, and their team used the intense magnetic field that accompanies the Z machine's electromagnetic pulse to squeeze liquid deuterium.

Researchers have caught signs of metallized hydrogen before. In 1996 Samuel Weir, Arthur Mitchell, and William Nellis used a gas gun to fire metal disks at liquid hydrogen and deuterium targets[2] to achieve shock-induced pressures up to 180 GPa (see PHYSICS TODAY, May 1996, page 17). For pressures greater than 140 GPa, they saw resistivity behavior indicative of a liquid metal.

However, those observations were at high temperatures—around 3000 K. Theorists think that the putative insulator-to-metal transition line terminates at a critical point somewhere in the vicinity of 2000 K. Most of the hydrogen was probably still in a molecular state, and the metallization was more a crossover than a transition. The Sandia–Rostock team wanted to duck under that critical point and cross directly through the transition line. "The biggest experimental challenge we had was how to reach the high pressures necessary while keeping the temperature low," explains Knudson.

The researchers figured that if they precisely shaped the Z machine's current pulse, they could combine two typical compression methods: shock and ramp. The initial part of the pulse magnetically launched an aluminum plate at the front face of an aluminum cryocell containing a 150-µm-thick layer of liquid deuterium cooled to 22 K. The shock reverberations from the 2- to 3.5-km/s impact heated the deuterium to between 800 K and 1400 K and drove pressure to 20–50 GPa. The remainder of the pulse, with its rising magnetic pressure, further compressed the sample along a gentler ramp so that the temperature remained below 2000 K, even as the pressure shot past 300 GPa.

The team chose to use deuterium rather than hydrogen for their first crack at crossing the insulator-to-metal phase boundary because deuterium's greater density made it easier to get the shock–ramp sequence right. Now that they have experience with their new technique, Knudson is confident that they can pull off a similar experiment with hydrogen.

## Shiny happy deuterium

The researchers used time-resolved optical techniques to monitor the pressure during their experiments. They then fed the measured pressures into theoretical models to estimate the temperature. The group also measured the deuterium's pressure response optically. The hallmark of a metal is that its freely flowing conduction electrons prevent electromagnetic waves from penetrating past the surface. Metallic deuterium, like any other metal, should reflect light.

Figure 2 shows the reflectivity of the sample relative to the reflectivity of aluminum, which was measured separately during the experiment. The Z machine's current pulse reaches the target roughly 1800 ns after the capacitors discharge. For times up to 2600 ns, the reflectivity ratio is essentially 1, which indicates that the deuterium was in its transparent, insulating molecular state and that reflection occurred at the interface between the sample and the cryocell's aluminum front face.

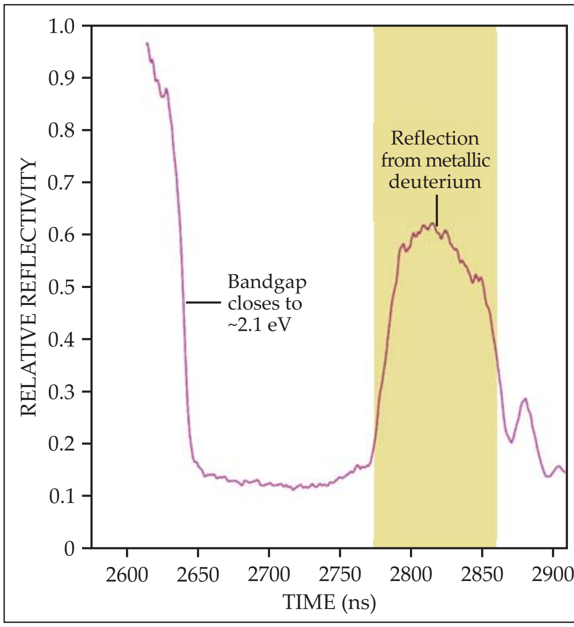


**Figure 2. Time dependence** of deuterium's reflectivity, normalized by the reflection from an aluminum film. At 2640 ns, when the pressure reaches 110 GPa, the deuterium suddenly loses transparency because its bandgap closes to energies that match visible wavelengths. Then, approaching 2775 ns, the reflectivity increases again, but the reflection is from the now-metallic deuterium. Past 2860 ns, the deuterium again becomes absorbing as the pressure decreases. (Adapted from ref. 1.)

Just past 2640 ns, when the pressure reaches 110 GPa, the reflectivity ratio suddenly drops. That behavior, say the researchers, is because deuterium becomes a strong absorber at visible frequencies as its bandgap closes to around 2.1 eV, the energy of a 590-nm photon. The reflectivity ratio recovers from 2775 ns until 2860 ns as the pressure shoots past and then dips back below 280 GPa. For those brief 85 ns, Knudson, Desjarlais, and company conclude that deuterium molecules have dissociated and the sample has become a shiny atomic metal.

"The experiments are certainly impressive, and the claims from the observations are important," says Paul Loubeyre of the Atomic Energy Commission in Saclay, France. But he cautions that past claims of hydrogen metallization haven't all stood up to scrutiny. Loubeyre says experiments using laser-shock techniques are already in the works to see if the new results can be reproduced. "The quest for metallic hydrogen is certainly not finished," he adds.

Yogendra Gupta of Washington State University agrees that confirmation is a must, but he's enthusiastic about the new results. "I think the evidence is quite strong," he says. "I'm struck by the care and rigor of the experiment and the enormous amount of theoretical work accompanying it."

In recent years many theorists have tackled the hydrogen metallization problem using density functional theory (DFT; see the article by Andrew Zangwill, PHYSICS TODAY, July 2015, page 34). The Sandia–Rostock group ran its own DFT calculations, and tried out two recently developed density functionals that add van der Waals interactions to more traditional implementations.

Most of the theoretical investigations agree that liquid hydrogen should undergo a first-order insulator-to-metal transition—one that involves latent heat—but they differ wildly on where the phase boundary should be. In the 1000- to 2000-K temperature range, different studies place the transition line anywhere from 100 GPa up to 600 GPa. Says Desjarlais, "It was clear to us that good data for the transition would provide a much needed benchmark for theories."

The insulator-to-metal phase boundary traced out by the team's four shots on the Z machine stays in a narrow pressure range close to 300 GPa between 1000 K and 2000 K. Desjarlais points out that commonly used density functionals that only treat electron correlations at a local level grossly underestimate the transition pressure. He thinks the new results point to the importance of longer-range van der Waals interactions. But he's quick to add, "It also suggests that there is more work to be done, because no one functional fits our data."

Gupta thinks the results should spur theorists to look for the missing ingredient in their models. "I see this work as opening a window into things we don't understand," he says. "But that's what keeps physics going."

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## References


1. M. D. Knudson et al., *Science* **348**, 1455 (2015).
2. S. T. Weir, A. C. Mitchell, W. J. Nellis, *Phys. Rev. Lett.* **76**, 1860 (1996).




# Imaging a mouse's brain through its skull

**A modest change in the application of adaptive optics to light microscopy produces a dramatic increase in the field of view.**

Biological tissues are rarely transparent. That fact has long complicated efforts by optical microscopists to resolve deeply embedded features, because the light waves used for imaging are scattered throughout the intervening tissue. The deeper the object, the more blurred the image. To ameliorate the problem, scientists in recent years have turned to adaptive optics: Using rapid, real-time analysis of a distorted-light signal, a computer-controlled deformable mirror or spatial light modulator compensates for aberrations in the optical path by reshaping the waves and thereby restoring crisp image detail.

Conventionally, the deformable mirror is placed at the microscope's so-called pupil plane—the back focal plane of the objective lens—where the mirror applies a uniform correction everywhere in the image plane. Such placement is appropriate, and provides the best focus, when the aberrations are spatially invariant, as is the case, for instance, when a refractive-index mismatch occurs along a flat interface. However, that condition doesn't hold in turbid biological tissue; and unless the deformable mirror actively adjusts the wavefront for different scanning angles through the tissue, a position mismatch develops between distortion and compensation. The result is a good focus over a very small field of view.

Like astronomers before them, microscopists can benefit from virtually placing the wavefront modulator in the scattering layer itself, where a point-to-point correspondence exists between mirror deformations and the aberrations they correct.[1] Meng Cui and collaborators at the Janelia Research Campus of the Howard Hughes Medical Institute have now applied that scheme, known as conjugate adaptive optics, to