Livermore's Big Guns Produce Liquid Metallic Hydrogen

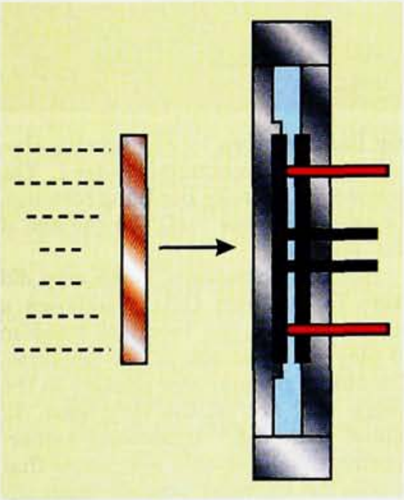
The seventy-year search for metallic hydrogen has demonstrated repeatedly that the hydrogen molecule's simplicity is deceptive. Three generations of theorists have predicted that sufficient pressure would squeeze a crystal of hydrogen into a metallic state, perhaps exhibiting exotic phenomena. Blithely ignoring most of these predictions, hydrogen at high pressures did indeed exhibit some remarkable behaviors, but it stubbornly resisted metallization.

Recently, metallic hydrogen and deuterium—in liquid form—made their terrestrial debuts in shockwave experiments at Lawrence Livermore National Laboratory.[1] Samuel Weir, Arthur Mitchell and William Nellis fired 25-millimeter metal disks from a two-stage gas gun at speeds of up to 7.33 kilometers per second into cryogenic targets. Each target contained a 0.5-mm layer of liquid hydrogen or deuterium sandwiched between two insulating sapphire anvils. (See the figure at right.) As the resulting shockwave passed from the anvils into the hydrogen, the shock pressure was initially diminished by a factor of 30 because of the density difference between the anvil and sample materials. Shocks reverberating between the two anvils then increased the pressure up to the initial pressure of the anvil shockwave—93–180 gigapascals in the various experiments—while keeping temperatures cool enough (2200–4400 kelvin) to ensure that the hydrogen molecules did not significantly dissociate. The resulting dense state reached equilibrium in less than a nanosecond and persisted for a few hundred nanoseconds, giving the experiment's fast electronics plenty of time to measure the sample's resistivity directly.

As the pressure increased from 93 to 140 GPa, hydrogen's resistivity dropped exponentially by more than three orders of magnitude, as expected for a semiconductor with a decreasing bandgap. In contrast, from 140 to 180 GPa, hydrogen behaved more like a liquid metal: Its resistivity leveled out at about 5×10^{-4} ohm-centimeters—a resistivity comparable to those of the alkali metals cesium and rubidium at comparable temperatures. (See the figure on page 18.) However, unlike the alkali metals, 95 percent of the hydrogen molecules at these temperatures should remain undissociated. Thus, the researchers concluded that hydrogen undergoes a phase transition to a molecular (probably H_2^+) metallic state, as first suggested by Cornell University theorist Neil Ashcroft. However, it does so in its liquid phase—at around 3000 K and 140 GPa, a temperature significantly higher, and a pressure significantly lower, than expected.

Metallic hydrogen has been a major goal for several generations of physicists. Now evidence suggests that this lightest of metals has been realized, but in an unexpected form.

In addition to providing the first evidence of metallic behavior in hydrogen, the results from Livermore have important applications in fields ranging from laser fusion to planetary physics. What is perhaps most significant, as the authors of the study stress, the results provide a window onto the behavior of ultrahigh-pressure hydrogen that complements that provided by diamond anvil experiments.



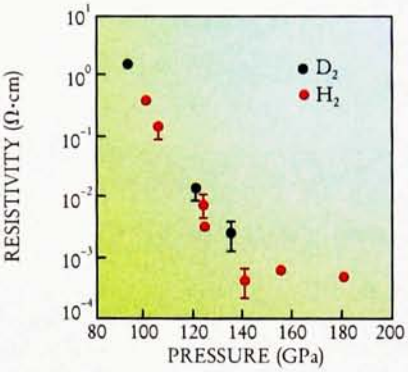
SHOCKWAVE EXPERIMENTS fire a hypervelocity projectile (reddish brown) at an aluminum cryogenic target (blue-gray), in which a 0.5-mm layer of liquid hydrogen (light blue) is sandwiched between two insulating sapphire anvils (dark blue). Resistivities are measured directly by insulated metal electrodes (black) as soon as the trigger pins (red) are crushed. Pressures are determined from the equations of state for the shocked projectile and target materials—the Hugoniot equations. Computer models are used to estimate temperatures and densities.

Complementary view

Largely because of hydrogen's rich variety of low-temperature quantum behaviors and because its bandgap decreases rapidly with increasing pressure, past theoretical treatments have concentrated on low-temperature, solid metallic hydrogen. However, the Livermore results indicate that the factors that inhibit metallization in the solid state at currently achievable pressures are diminished or eliminated by high temperature and melting.

High-pressure diamond anvil experiments, like the theoretical studies, have concentrated on crystalline hydrogen at low-to-ambient temperatures, although for more practical reasons: High temperature exacerbates hydrogen's already strong tendency to penetrate and break diamonds. In view of Livermore's results indicating the importance of temperature in hydrogen metallization, and because shock experiments cannot achieve significantly lower temperatures, Ashcroft has emphasized the importance of extending diamond-anvil investigations to higher temperatures, as well as higher pressures.

The shockwave experiments also highlight the advantages of direct conductivity measurements in detecting metallic transitions. Some researchers have raised the possibility of using microlithography on diamonds to make such measurements possible inside diamond anvils. Current diamond anvil research relies on optical methods, such as ultrahigh-pressure spectroscopy, to measure the vibrations and rotations of H_2 molecules within the crystal.[2] These measurements have yielded possible evidence for several factors that may suppress metallization, including strong proton–electron coupling, magnetic ordering of the electrons, intermolecular electronic interactions and perhaps even charge transfer and quantum tunneling of protons. However, detecting metallization with optical techniques is not a straightforward process.



METALLIZATION of hydrogen (red) and deuterium (black) is evident from the leveling out of resistivity as a function of pressure and by the low measured resistivities, which are similar to those of some liquid metals at comparable temperatures.

Applications and future progress

For now, however, the discovery of metallic hydrogen under conditions of high temperature and relatively low pressure will probably be most influential outside of high-pressure physics. According to Nellis, the Livermore shockwave experiments measure the density dependence of the bandgap under conditions similar to those in the initial stages of fuel-pellet irradiation in laser fusion. These data show that electronic excitations of the fuel pellet's hydrogen absorb more energy than was thought previously. Because energy absorbed by electronic excitations does not heat the fuel, this implies higher compressibility and higher laser-fusion yields than expected.

The results also have important implications well beyond the laboratory. According to Caltech planetary physicist David Stevenson, they are particularly welcome among planetary physicists trying to account for the high magnetic fields of hydrogen-rich giants Jupiter and Saturn. The onset of metallization at lower-than-expected pressures implies that the dynamos generating the magnetic fields are located much closer to the surface than previously thought. Because the roughly dipole magnetic field generated by the dynamo decays approximately as the inverse cube of distance, a near-surface dynamo need not generate unreasonably large fields. Similar considerations probably also apply for the planets recently discovered orbiting the stars 51 Pegasi, 70 Virginis and 47 Ursae Majoris, although the nearness of these planets to their respective stars places them in another temperature regime. (See PHYSICS TODAY, March, page 9.)

In future shockwave experiments, Weir, Mitchell and Nellis hope to probe such higher temperature conditions, as well as to continue checking their results by using different anvil and sample materials. Given their recent findings, one looks forward to what they may achieve as an encore.

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References

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Measuring Distances to More Supernovae Sharpens the Hubble Constant Debate

A recent *Astrophysical Journal* letter by veteran astronomer Allan Sandage (Carnegie Observatories, Pasadena, California) and coworkers[1] offers some solace to troubled adherents of the cosmological scenario most favored by the theorists. The contentious observational issue is the value of H_0, the Hubble constant. A variety of measurement schemes that use properties of galaxies have in recent years put H_0 between 80 and 85 km/s per megaparsec. (A megaparsec is 3.3 million light-years or 3.1×10^{19} km.) But Sandage and company, using supernovae, have long held out for a value closer to 50 km/(s·Mpc). "Our new paper," Sandage contends, "is the beginning of the end of the Hubble-constant wars."

Other groups that also use supernovae question Sandage's finality and argue that he somewhat underestimates H_0. But like him, they also find H_0 to be well below 80 km/(s·Mpc). This troubling discrepancy between two different but equally respectable classes of techniques remains, in the opinion of most of the cognoscenti, a puzzle still to be resolved.

The stakes are high. In the general cosmic expansion, the recessional velocity of any sufficiently distant galaxy is proportional to its distance from the observer. H_0 is the proportionality constant. The total elapsed time since the Big Bang is given by H_0^{-1} times a theory-dependent constant of order 1. The favored inflationary Big Bang scenario, for example, gives $\frac{2}{3}H_0^{-1}$ for the age of the universe.

Measuring the Hubble constant with supernovae continues to suggest an older universe than one gets with other yardsticks.

But the existence of some very old stars in our own Galaxy imposes a severe limit on the theorists' freedom to play with the age of the universe. The oldest globular star clusters in the Milky Way are, at the very least, 12 billion years old.[2] It becomes embarrassing to adhere to a cosmology that makes the universe younger than our local globular clusters. Inflationary Big Bang cosmology, or any other scenario with critical closure mass density, requires that H_0 be no larger than about 54 km/(s·Mpc), if the universe is to be older than 12 billion years. If H_0 turns out to be bigger than about 80 km/(s·Mpc), no Big Bang scenario yields an age greater than 12 billion years unless it invokes a nonvanishing "cosmological constant"—a kind of universal repulsion that would work against gravity.

Standard supernova bombs

The new paper by Sandage *et al.*[1] reports an H_0 of 57 ± 4, just barely consistent with Big Bang theories with the desired critical closure density and vanishing cosmological constant. To measure the Hubble constant, one needs a collection of cosmologically distant objects for each of which one knows both the recessional redshift and, independently, the distance. To that end, the Sandage group avails itself of type Ia supernovae, whose distinguishing signature is the absence of hydrogen in their spectra. The intrinsic luminosity of type Ia supernovae at peak brightness, a few days after the explosion, is thought to vary relatively little from case to case. That's because they are all believed to be exhausted white dwarfs that accrete additional mass from a partner until they suddenly blow up somewhere near the so-called Chandrasekhar limit—about 1.4 solar masses. Just how much variation there is within the type Ia class, and what one needs to do about it, is a subject of voluble contention between Sandage and other groups seeking to determine the Hubble constant by means of supernovae. In any case, type II supernovae, with a considerable range of ignition masses and residual cores, exhibit a much greater variation of intrinsic luminosities than the type Ia's.

To the extent that type Ia superno-