Metallic Hydrogen: Simulating Jupiter in the Laboratory

At pressures and temperatures found on the earth hydrogen is a gas and it becomes solid when cooled to temperatures below 14°K. But under extremely high pressures hydrogen may become a metal, and metallic hydrogen is commonly thought to constitute as much as 40 percent of the mass of the planetary system—particularly in the massive planet Jupiter. Yet estimates of its basic properties, such as melting temperature and solubility with other elements, are quite uncertain. Better information would improve the current models of Jupiter and Saturn, which are now said to be "in terrible shape," according to one researcher, and more pragmatic visionaries have suggested that metallic hydrogen could be a very useful rocket fuel, because of its expected high density. For the same reasons, metallic deuterium could be very useful for processes that utilize fusion energy, such as weapons construction and thermonuclear power production. It is even possible that metallic hydrogen could be a superconductor at room temperature, and several utility companies are said to be closely watching attempts to produce it in the laboratory.

The notion that a gas can be solidified and forced into a metallic state at very high pressures is not new. In 1926 J. D. Bernal suggested that any element becomes a metal at high enough pressures. Particularly, for a diatomic molecule such as hydrogen, the intermolecular distance decreases with high pressure until an individual atom does not know whether it belongs to its own molecule or to the next one, and the material becomes metallic with all atoms approximately equidistant and all electrons uniformly distributed. Harry G. Drickamer, at the University of Illinois, in Urbana-Champaign, found 10 years ago that an analogous change occurs for iodine, which is also a diatomic molecule. Iodine undergoes a transition from a diatomic crystal to a solid metal at a pressure above 170 kilobars (1 bar is atmospheric pressure). Estimates of the pressure necessary for hydrogen to become a metal have varied widely, but at least 1 megabar (Mbar) of pressure is usually assumed necessary. However, there were very few experimental studies of hydrogen at such high pressures until recently.

In the last year, however, Russian experimenters have measured the compressibility of hydrogen at pressures ranging from 0.4 to 8 Mbar (*1*) and have reported a sudden increase in the volume at 2.8 Mbar, which they suggest is evidence for the formation of a metallic phase. What the Russians actually measured was an increase in the density from 1.08 to 1.3 g/cm^3. (No discontinuity in density appears as iodine becomes metallic.) According to Roman Smoluchowski of Princeton University, Princeton, New Jersey, a change to a more dense state is expected during the transition to a metal, but more direct evidence is needed to show that a metal was actually formed. Ronald S. Hawke, John G. Huebel, and collaborators at the Lawrence Livermore Laboratory, Livermore, California, have also recently examined hydrogen at a pressure of about 2 Mbar, but have not yet determined the compressibility over a large pressure range. Huebel and associates at Livermore hope in the near future to measure electrical conductivity, in addition to pressure and volume, in order to establish whether a transition from an insulator to a metal takes place.

Russian Report of Metallic Hydrogen

Very few details are known about the Soviet experiment, which was performed at an unnamed institute believed dedicated to weapons research. No picture of the experimental apparatus is presented in the Soviet paper, but the technique for compressing hydrogen employs a cylindrical charge of explosive and proceeds without changing the entropy of the hydrogen sample. The volume of the hydrogen cell, which initially contains gaseous hydrogen, is measured during compression by gamma radiography, but the method by which pressure was measured is not described, nor are any errors assigned to the pressure measurements.

Grigor'yev and his associates calculated a theoretical curve for the compression of molecular hydrogen in a process that conserved entropy, and found that it described the data well at pressures less than 2.8 Mbar, but had to be modified for higher pressures. "We can satisfactorily describe all available experimental data if we assume that the transition to the metallic modification of hydrogen in the solid state occurs at pressure $P \sim 2.8$ Mbar with a jump in density from 1.08 to 1.3 g/cm^3," the authors said. However, they calculated that the temperature at which the anomaly occurred was so high (7000°K), that "we cannot identify the break in the experimental curve with the solidification of hydrogen," and so they suggested that the anomalous transition occurred in the liquid phase of hydrogen.

The experiments of Hawke and his associates at Livermore are apparently similar to those of Grigor'yev and colleagues (a coaxial explosive is also used in a process that conserves entropy), and much more is known about them (*2*). The key to the Livermore technique is compression by a rapidly changing magnetic field, as suggested by F. Bitter in 1965. The sample of hydrogen is placed inside a copper cylinder $\sim$ 1.3 cm in diameter, which is inside a larger stainless steel cylinder $\sim$ 10 cm in diameter. The stainless steel cylinder is surrounded by high explosive. Just before the explosive is fired, a strong (60 kilogauss) magnetic field is generated in the space between the two cylinders. As the stainless steel cylinder implodes, the magnetic flux is trapped in an ever-decreasing area, with the result that the magnetic field intensity increases to about 10 megagauss in about 10 microseconds. The magnetic field generates a smoothly increasing pressure on the cylinder containing hydrogen. The maximum pressure reached with the Livermore device is about 4 Mbar.

The volume of the hydrogen sample is measured with two very fast x-ray exposures before and during the compression. From these pictures the density can be determined. The maximum density that Huebel and associates have reported for hydrogen is about 1 g/cm^3, or about 14 times the density of liquid hydrogen, which was the original sample. Pressure is far more difficult to measure than volume in such experiments. It was determined indirectly, by measuring the amount of compression of the stainless steel cylinder, to be 2 Mbar, but the error assigned was very large, 1 Mbar.

The experiments with magnetic compression proceed slowly enough that no shock wave is formed in the hydrogen sample. However, an older technique is to deliberately compress the sample with shock waves. In a separate program at Livermore, shock wave techniques have been used to reach a pressure of 0.9 Mbar, according to Mathias Van Thiel. However, entropy increases during compression by a shock wave, and after a certain limiting volume the shock stops compressing and only heats. Shock techniques produce very high and well-defined pressures in stiff materials such as iron, but are much less effective for a substance as soft as hydrogen.

If metallic hydrogen were produced by dynamic techniques, such as magnetic or shock compression, there would be little chance to recover it afterwards if the metallic form were stable at more normal pressures. However, metallic hydrogen might be recovered in a metastable state if it could be produced by a static technique, such as compression with a large press. The Soviet Union has an Institute for High Pressure Physics, which purportedly plans a 10-story-high press. Leonid Vereschagin, head of the institute, plans to use the press to reach 2 to 3 Mbar in an attempt to make metallic hydrogen. At Cornell, Arthur Ruoff is preparing experiments with an "opposed anvil" press that should reach 3 Mbar. N. Kawaii, at the University of Osaka, Japan, has an ingenious device, consisting of a sphere split into octants with crushable spacers between them, to perform experiments with a static press. At the University of Maryland, Ian Spain is setting up an experiment using the Kawaii technique. One problem with the static techniques is finding ways to introduce diagnostic instruments into the pressurized chamber. Another problem is calibrating pressures at very high values. Although temperature scales are well linked by different physical laws, fundamental relations of pressure to different physical phenomena are much harder to establish. However, theoretical calculations indicate that although the metallic form would not be the lowest energy state of hydrogen, there would be an energy barrier (about 0.2 electron volts per electron) to prevent it from returning to the molecular state. According to Neil Ashcroft of Cornell University, Ithaca, New York, metallic hydrogen should be metastable in a practical sense, with a density of about 0.6 g/cm^3. (A less extreme example of metastability is diamond, which is not the lowest energy state of carbon, but is formed at high pressure and remains stable when the pressure is released.)

Ashcroft also notes that, according to the Bardeen-Cooper-Schrieffer (BCS) theory of superconductivity, metallic hydrogen may be a high-temperature superconductor (*3*). Although most alkali metals are thought to have no superconducting transition within the range of current low-temperature techniques, metallic hydrogen might be superconducting at room temperature because it is expected to have a very high Debye temperature (3500°K), and the phenomenon responsible for pairing (electron-phonon coupling) is not otherwise abnormal. If hydrogen were metastable in the metallic phase and were also a superconductor at room temperature, it could have many practical applications. Even if metallic hydrogen were not metastable, the question whether it is superconducting could have some significance for astrophysical bodies so massive that the internal pressures exceeded several megabars.

What Is Jupiter's Heat Source?

The pressures in the interior of Jupiter are thought to reach 100 Mbar, and few scientists now doubt that much of the planet is metallic hydrogen. The mass and radius of Jupiter are well known, and these values severely limit the possible compositions for the planet. You simply cannot get the mass to come out correctly by assuming a composition of molecular hydrogen (the density of molecular hydrogen at atmospheric pressure is 0.071 g/cm^3 and the density of metallic hydrogen is expected to be 0.64 g/cm^3). Most scientists who have proposed models for Jupiter assume that the transition to a metallic state occurs at a radius equal to about 0.8 or 0.85 of the surface radius, and the density of the core is discontinuous. Jupiter probably consists by mass of about 80 percent hydrogen, almost 20 percent helium, and a few percent of heavier elements. (These estimates are similar to estimates of the composition of the presolar nebula from which the solar system was formed.)

While the pressure and density profiles of Jupiter are fairly well known, the profile of temperature at different depths in the planet is not. Estimates of the maximum central temperature range from a few thousand to 30,000°K. Not only is the actual temperature poorly known, but the melting temperature of metallic hydrogen is also poorly known. (The uncertainty in theoretical estimates is at least 10 to 15 percent, according to Smoluchowski.) There is no agreement at all whether the interior (or even the surface) of the planet is solid or liquid. Another problem with models of Jupiter is that the source of the heat emitted by the planet is not known. Whereas the earth absorbs from the sun nearly the same amount of heat as it radiates away, Jupiter radiates almost three times as much heat as it absorbs. Three sources of heat have been proposed. First, the planet may still be losing primordial heat stored during its formation. A second proposal is that the surface may be contracting slowly. The gravitational potential of Jupiter is so great that a surface shrinkage of only 1 mm per year would supply all the energy radiated into space. A variation of this idea, proposed by Smoluchowski, is that the boundary between metallic hydrogen and molecular hydrogen may be shifting slowly outward. If the radius of the metallic core increased by about 1 mm per year at the expense of the molecular region, the result would be that the whole planet would shrink and release energy.

A third proposal for the heat source in Jupiter, recently suggested by E. E. Salpeter of Cornell, is that helium and liquid metallic hydrogen may be mixed in the hot interior of the planet, but that in some cooler intermediate layer they slowly unmix. Droplets of heavier helium sink to the core of the planet, thus releasing gravitational energy (*4*). However, the solubility of helium in liquid hydrogen at very high pressures is not at all well known, so Salpeter's model is still qualitative. Since most models for Jupiter feature a fluid interior unstable against convection, it had generally been assumed that chemical separation and gravitational layering were impossible. Convection is such a rapid process that it would destroy the layering. However, Salpeter points out that if helium becomes insoluble in hydrogen, layering (and the subsequent release of gravitational energy) may take place in spite of convection.

For a variety of reasons, many researchers in the United States are joining the band that is searching for metallic hydrogen. Almost without exception the experiments are difficult to execute and interpret. By contrast, theoretical calculations far outnumber experiments. The next few years should prove whether or not the metallic predictions will ring true.

—William D. Metz

References

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