The Revealing Role of Pressure in the Condensed Matter Sciences

Experimenters can now change the densities of condensed matter by upward of an entire order of magnitude, and thereby impart dramatic changes in physical and chemical properties of materials.

Russell J. Hemley and Neil W. Ashcroft

Matter in bulk has both a microscopic and macroscopic description, with the latter going back to the very earliest days of thermodynamics. Of the common thermodynamic variables pressure (p) and temperature (T), it is temperature that has played by far the most prominent role in probing condensed matter and in our fundamental understanding of it. However, even as far back as 1660, Robert Boyle declared in his famous treatise commonly known as *Touching the Spring of the Air* that "perhaps the pressure of the air might have an interest in more phenomena than men have hitherto thought." More than three centuries later, we can see how right he was, as systematic use of pressure has led to considerable insight into the properties of matter, especially its electronic properties. As A. Jayaraman noted when he was at AT&T Bell Laboratories, of all physical variables, pressure possesses one of the greatest ranges—over 60 orders of magnitude. At the high end, the pressures are those of the interiors of neutron stars; at the other, they gauge the conditions of the remotest vacua of outer space. And as Claude Berthelot demonstrated in early experiments on simple fluids, the pressure is not even obliged to be positive. (Negative pressure is created by, for example, pulling on the surface of a solid or on a wall of a sealed vessel full of fluid.)

Recent experimental advances now allow us to change densities in the condensed state by more than an entire order of magnitude.[1] It is through pressure, which is a special case of generalized stress, that one can change the volume of a system or the average particle density. The changes may be brought about in a quasi-static way, typically nowadays by the use of diamond-anvil cell devices. (See figure 1.) Or they may be brought about dynamically, through the use of shock methods, which are accurate techniques that have been in existence for over five decades. (See figure 2.) In either case, the atoms in condensed forms of matter are driven closer together. As first observed by Percy Bridgman of Harvard University in 1926, this compression offers a route to "breaking down" the electronic structure of the atoms themselves and to the possibility of entirely different bulk properties. Through application of pressure, we can bring about one of the most basic of all changes, the crossing of the "great divide" from insulators to metals.

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On the atomic level

The fundamental problem that pressure elucidates becomes clear if we take a pure element as an example. For macroscopic quantities of an element, the basic Hamiltonian at the level of elementary nuclear and electronic charges is

$$\hat{H} = \hat{H}_{nn} + \hat{H}_{en} + \hat{H}_{ee}, \tag{1}$$

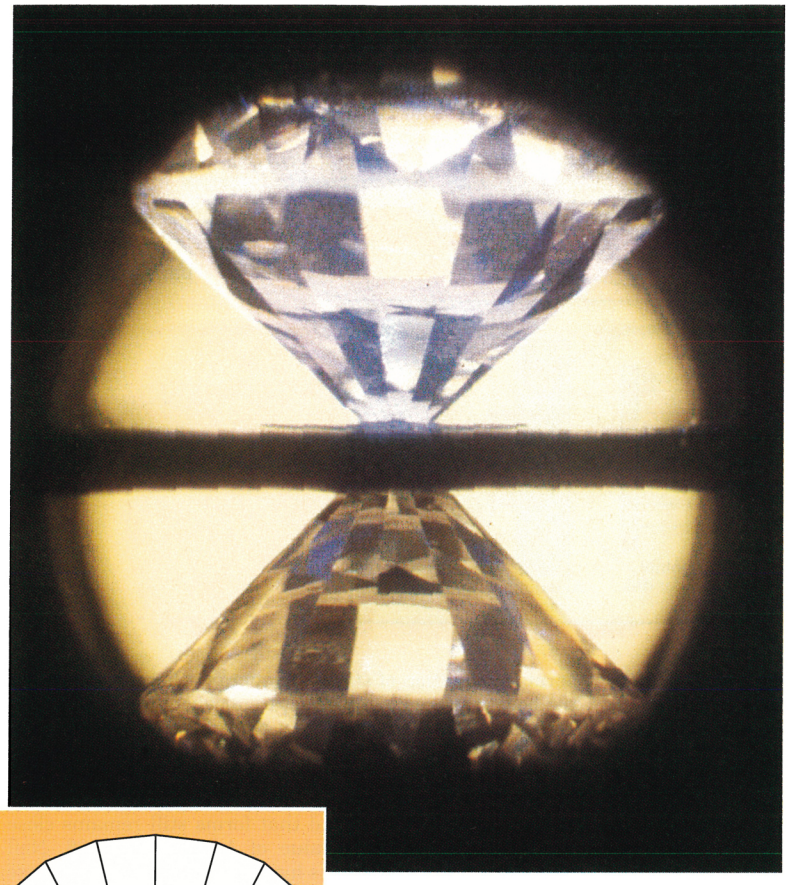
where $\hat{H}_{nn}$ and $\hat{H}_{ee}$ are the kinetic energy of the nuclei and the electrons, respectively, augmented by their mutual Coulombic potential energies; the third term represents the mutual Coulombic attractions. The entire assembly is held in a volume V, and as a consequence of this confinement boundary condition, the stationary states of the fundamental Schrödinger equation,

$$\hat{H}\psi(V) = E(V)\psi(V), \tag{2}$$

are very clearly functions of volume V and hence alterable by pressure.

The manifestly complex many-body problem embodied in equation 2 is quantum mechanical from the outset and has been modeled in many ways. In systems where the electrons are highly localized, for example, the electrons can be approximately accounted for by incorporating their major influences into effective adiabatic interatomic potentials that subsequently control the motions of atoms or molecules. Alternatively, the electrons in the element under examination may be spread out, in which case an energy-band picture would be more appropriate. Pressure alters both bandwidths and bandgaps, and offers a way to refine both—that is, pressure acts as a probe of band structure. Here, band structure is a one-electron rendition of the more general problem represented by equation 2, which is now being attacked by increasingly powerful electronic structure methods. Moreover, depending on choice of thermodynamic conditions, we know that the states of equation 2 can also be electronically ordered, exhibiting magnetic states or superconducting states, for example. Pressure can initiate such order and is a revealing diagnostic tool.

Condensed matter is not easily compressed, in part because of its fundamental scale: An atomic unit of pressure is $e^2/2a_0^4$, and this measure has the practical (and large) value of 147.2 million atmospheres, or 14 720 gigapascals (1 GPa = 10 kbar). And yet, as Harry Drickamer of the University of Illinois at Urbana–Champaign has observed, if a few kilobars of pressure produce a large effect in some property of a system of, say, large, tortuous but not



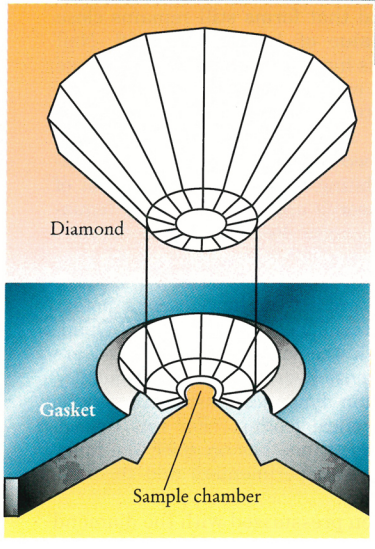


FIGURE 1. THE DIAMOND-ANVIL CELL has emerged as the dominant and most versatile tool for achieving ultrahigh pressures. It uses two diamond anvils, which exert pressure and serve as windows on the sample. A metal gasket confines the sample and supports the anvils, as the diagram indicates. Pressure is simply force divided by area, and so large pressures can be produced by reducing the area over which a force of relatively modest proportions is directed. Because diamond is the strongest material known and is transparent over a wide range of the electromagnetic spectrum, pressures above 300 GPa (3 megabars) can be reached and studied. Some of the most important diamond-anvil-cell measurements are those that exploit the high brightness of synchrotron radiation and laser techniques. (Photo by Jinfu Shu, Carnegie Institution of Washington.)

very compact molecules, such as biomolecules, then this effect can surely be taken as high pressure.

Pressure induces myriad changes in materials. First, compression typically causes a tendency toward the closer packing of atoms, ions or molecules. Although this is often assumed to mean a corresponding tendency toward simpler structures, sometimes quite the opposite is true. Indeed, pressure may induce order, but it also can bring about disorder (as is discussed below). Generally, one of the simple ways in which compression can be achieved is by increasing the local coordination number—for example, by progressing from tetrahedral to octahedral coordination of silicon by oxygen in silicates. This increase in turn is intimately linked to changes in electron hybridization—the electronic problem represented in equation 1. As hinted above, such changes can be associated with major changes in electronic and magnetic states, including the formation of conductors or superconductors from materials originally possessing substantial bandgaps. Finally, in various ways such changes all affect chemical behavior: Pressure can induce chemical reactions that do not occur under more familiar conditions, and it can speed up or slow down known chemical reactions.

Although many of these effects of pressure on condensed matter have been known for years, it is only recently that the full potential of the pressure variable in the condensed matter sciences has begun to be realized. This change is due to striking advances in experimental high-pressure techniques. The imagined applications of pressure are clearly as broad as the range of condensed matter itself.[1] Accordingly, it is useful to illustrate the major physical points with a few examples showing the manner in which the states of equation 2, and its extension to compounds, are significantly changed by altering a simple mechanical variable—namely, p.

Crossing the great divide

The behavior of ionic salts and rare-gas solids at very high pressures exemplifies many high-pressure phenomena. Cesium iodide is an ionic salt with a simple cubic structure with a two-point basis, conventionally described as the closed shell ions Cs^+ and I^-. Two atoms of the rare gas xenon are isoelectronic with CsI and condense either at low temperature or at moderate pressure to form a cubic crystal, but its structure and bonding are entirely different. The atoms are neutral, crystallize in the face-centered cubic structure and are bound by weak van der Waals forces, an attractive interaction arising from the average of the instantaneous mutual polarization of electrons on adjacent atoms.

These materials—ionic salts and rare-gas solids—have now been subjected to pressures well above 100 GPa, using both static and shock-wave methods.[2] For several years, the results of both kinds of experiments differed significantly, but now they are in excellent agreement. What happens on compression is remarkable. First, as revealed by synchrotron x-ray diffraction experiments carried out with diamond-anvil cells, despite the different initial densities, the pressure/volume relations converge under pressure to such a degree that they are indistinguishable above 50 GPa. (See figure 3.) Second, as shown by the same experiments, with increasing pressure, both materials reveal crystallographic transformations and take on the hexagonal-close-packed structure at the high-

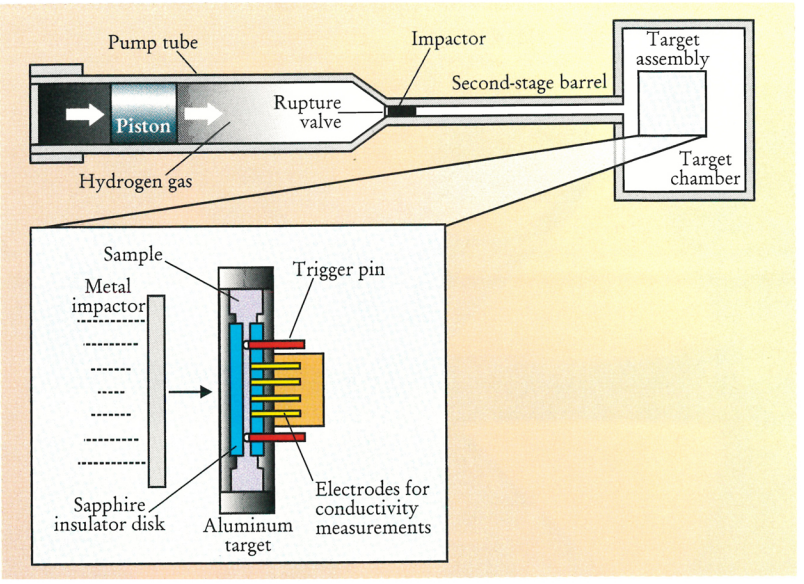


FIGURE 2. SHOCK-WAVE COMPRESSION scheme for achieving ultrahigh pressures. The diagram shows the layout of the light-gas gun at Lawrence Livermore National Laboratory. The target assembly shown is for conductivity measurements on fluid hydrogen at high pressures and temperatures. (Adapted from refs. 6, 9.)

est pressures. From the standpoint of x-ray diffraction, for example, the cesium and iodine ions appear as essentially equivalent. Third, as has been demonstrated by optical reflectivity and absorption measurements, the electronic properties change fundamentally: Between 100 and 150 GPa, both evidently cross the great divide of bulk matter—namely, from the insulators to the metals. Hence, despite their very different birthrights—one a compressible ionic crystal, the other a weakly bound van der Waals solid—both materials transform to hexagonal-close-packed metals with identical densities at megabar pressures.

Pressure-induced insulator-to-metal transitions have been documented in a long list of materials and over a broad range of pressures, from low pressures of much less than 1 GPa to high pressures well above 200 GPa.[1] One of the most well-studied of these materials is the technologically critical element silicon, which transforms at low temperatures (it is a metal in the fluid state) from the familiar diamond-type semiconductor phase to the metallic β-tin structure at 12 GPa. As pressure increases further, there follows a sequence of transitions culminating in the face-centered cubic structure, which is then stable to at least 300 GPa.

A quite different class of insulator/metal transitions is illustrated by iodine, which forms a diatomic molecular solid at normal conditions but transforms to a metallic phase under pressure while still essentially preserving its molecular state. In fact, iodine also exhibits a sequence of crystallographic transitions culminating in the formation of a face-centered cubic metal at about 50 GPa, this structure persisting well into the multimegabar range (to at least 275 GPa).[3]

Silicon and iodine are of interest for another reason. They share a striking property common to many of the "new" metals formed under pressure: Several high-pressure phases of silicon and also the dense face-centered cubic phase of iodine are superconductors at low temperatures.[1,3]

Element one

The behavior of molecular solids under pressure leads naturally to one of the preeminent goals of high-pressure research—to elucidate the potentially rich high-density physics of the most abundant element, hydrogen. Among the elements in condensed form, hydrogen is unique. It is the only quantum molecular solid, with molecules that are so light and that initially interact so weakly that they freely rotate in the one-atmosphere crystal, even at the lowest temperatures. And the molecular solid formed by those molecules is a tenacious insulator.

Eugene Wigner and Hillard Huntington of Princeton University predicted in 1935 that at extreme pressures, hydrogen molecules would dissociate in favor of a monatomic metal. Their one-electron treatment of equation 2 led to the prediction of a new minimum in the low-temperature equation of state (the energy/volume relation) for the body-centered cubic structure at about eight-fold compression. But their seemingly plausible assumption, that a Bravais lattice structure could exist at this compression, is now known to be incorrect. Even at this high density, the ensuing lattice remains unstable to pairing of protons, and the length of the bond that forms still remains close to the one-atmosphere value of 1.4 a_0. In 1968, Neil Ashcroft predicted that this hypothetical monatomic phase of dense hydrogen would exhibit unusual properties, including very high temperature superconductivity as well as a liquid-like ground state. More interestingly, theory indicated that hydrogen may become metallic prior to dissociation of the molecules, exhibiting behavior similar to that of iodine. But despite the theory's apparent simplicity (equation 1, for example), an accurate description of hydrogen's possibly unique "quantum metallic" properties, and the precise determination of the transition and other remarkable transitions now known to precede it, have been a potent challenge to state-of-the-art condensed matter theory. Quantum effects associated with the low mass of protons are particularly significant in dense hydrogen, and consequently, electron dynamics and proton dynamics must eventually be treated on the same theoretical footing. For this reason, putting the squeeze on element one has occupied the fancy of high-pressure researchers—experimenters and theorists alike—for over half a century.

Hydrogen has now been pressurized with the diamond cell, at relatively low temperatures, to the 300 GPa range,[4] yielding a more than 12-fold solid compression[5] and revealing behavior far more remarkable than expected. Unlocking the secrets of hydrogen along the path toward the eventual quantum metallic state has been a story not only of sleuth but also of constant surprise. Spectroscopic measurements show that the molecular bond is indeed, as noted, a tenacious one: The molecular state of hydrogen persists to remarkably high pressures. Although pairing of the protons clearly prevails, striking changes in physical properties occur over this substantial range of compression. Infrared spectroscopy reveals a three-orders-of-magnitude increase in absorption of the intramolecular stretching mode at a phase transition found at 150 GPa (figure 4).[4] This increase is extraordinary because such absorption vanishes by symmetry in the isolated molecule. At the same point, there is a decrease in the frequency

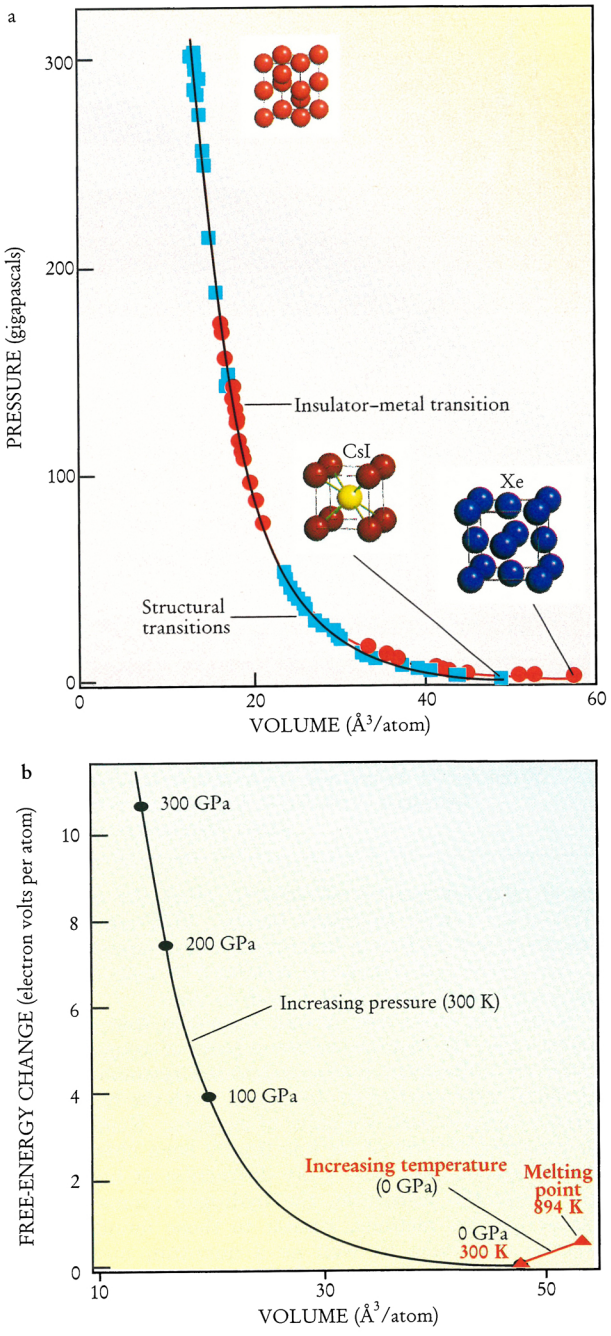


FIGURE 3. STRUCTURAL CONVERGENCE of cesium iodide and xenon (**a**), and CsI free-energy function (**b**). **a:** Though starting with different structures, cesium iodide is isoelectronic with atoms of xenon. Despite these differences, there is a striking convergence of corresponding equations of state at high pressure. Both systems undergo transitions culminating in metallic band-overlap states. The low-pressure crystal structures of cesium iodide (simple cubic) and xenon (face-centered cubic) are also shown. For cesium iodide at high pressure, diffraction patterns indicate a hexagonal-close-packed structure, with the Cs and I atoms (which are indistinguishable in the high-density state) arrayed on the lattice points of the hexagonal-close-packed structure. (Compilation of data from ref. 2.) **b:** The effect of pressures reached in current static-compression experiments on the energetics of solids is typically much greater than the effect of temperature. The contrast is evident in this plot, which compares the Helmholtz free-energy change in CsI due to compression at room temperature with the change due to heating to the melting point at room pressure. (After R. Jeanloz, Ann. Rev. Phys. Chem. 40, 237, 1989.)

of the vibrational mode.

The changes now being observed in hydrogen can be understood in terms of a series of symmetry-breaking transitions with increasing pressure and decreasing temperature. According to recent theoretical interpretations, one of these transitions involves a breaking of electronic symmetry in the proton pairs, a state of spontaneous polarization akin to that in an antiferroelectric material. This transition actually leads to an increase in bandgap, the quantity that pressure generally works to close. Extrapolations of the downward progressing stretching-mode frequency and the rapidly upward progressing zone-boundary optical phonon indicate that the monatomic instability cannot be too far from present static pressure capabilities.

In the past two years, striking new results in hydrogen have also come from dynamic compression experiments. Techniques have been developed in which the pressure in the compressing sample is made to ring up to higher values without the problematic increase in temperature that conventionally occurs in shock-wave compression. Recent conductivity measurements in such an experiment at Lawrence Livermore National Laboratory show evidence for conducting behavior at 140 GPa and 3000 K in the high-temperature *fluid*.[6] (See figure 5.) The onset of conductivity is close to the pressure where marked changes in the solid's physical properties take place.

A second experiment, also at Livermore, accessed still higher temperatures using ultrahigh-powered lasers to send a shock wave through the sample.[7] The experimenters observed a density collapse and interpreted it as arising from dissociation of the molecules. It must be said that metallization of the system, defined as the point at which the DC conductivity becomes finite as $T \rightarrow 0$, remains to be observed, by any technique. Yet, because the dense high-temperature fluid is being probed in these dynamic compression experiments, the results have significant implications for our understanding of the interiors of the giant planets. Jupiter, for example, is about 90% hydrogen, most of which is at ultrahigh pressures in a fluid metallic state. The evidence for a conducting fluid at pressures lower than previously thought extends considerably the previously assumed radial extent of the conducting region of Jupiter. The results can now further assist in understanding both the luminosity of the planet and the origin of its large magnetic field, which is generally believed to be associated with fluid metallic hydrogen within the planet's mantle.

Puzzles and polymorphism in water

Two-thirds hydrogen by number, H_2O is clearly one of the most important of substances, ubiquitous in biology and the environment. In the condensed phase, it shares with hydrogen the property that it is also one of the most difficult substances to understand. Recent high-pressure experiments not only have revealed profound changes in its character at high density, but also have documented new and again surprising phenomena.[8–10] In the condensed phase—that is, in liquid water and the large number of ices documented at low temperatures and moderate pressures—the oxygen atom of each molecule is covalently, and strongly, bonded to two hydrogen atoms. (See figure 6.) At larger distances are found two hydro-

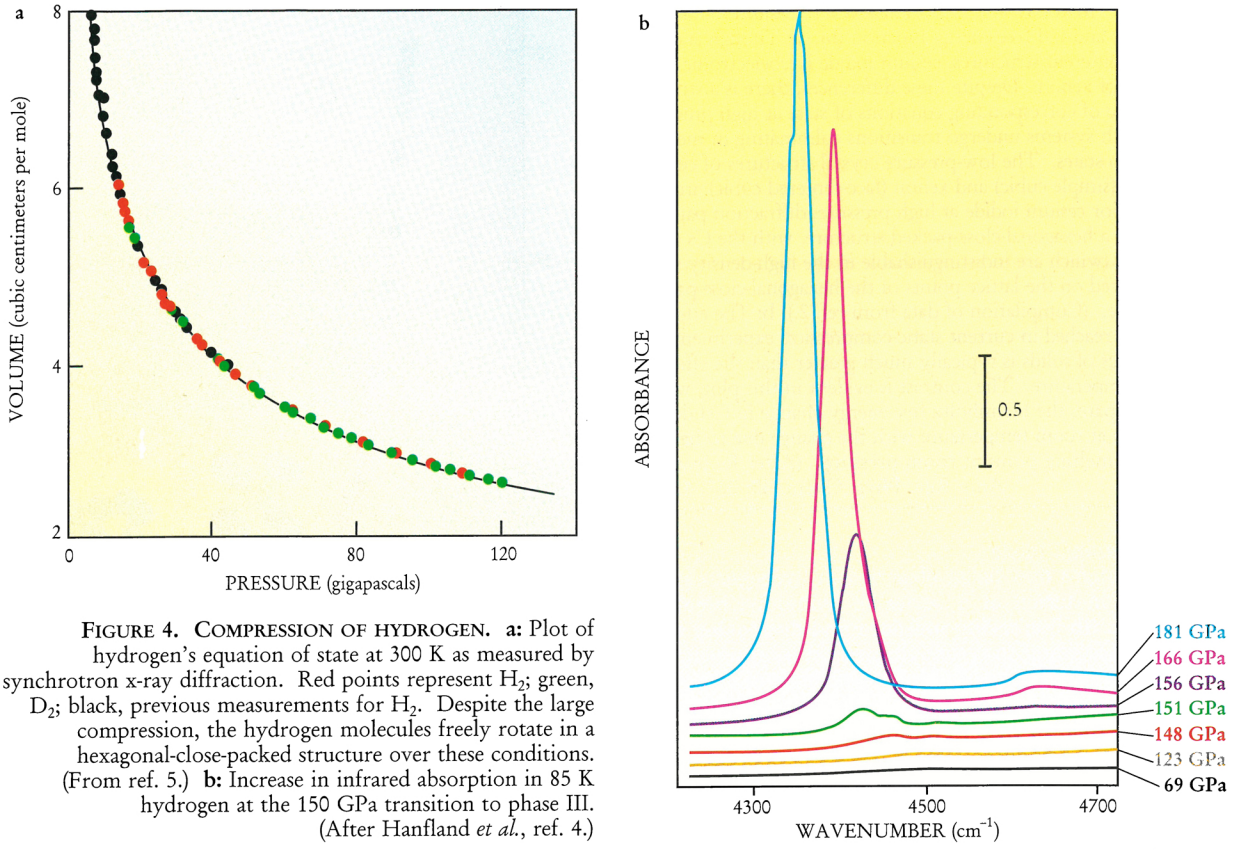


FIGURE 4. COMPRESSION OF HYDROGEN. **a:** Plot of hydrogen's equation of state at 300 K as measured by synchrotron x-ray diffraction. Red points represent H_2; green, D_2; black, previous measurements for H_2. Despite the large compression, the hydrogen molecules freely rotate in a hexagonal-close-packed structure over these conditions. (From ref. 5.) **b:** Increase in infrared absorption in 85 K hydrogen at the 150 GPa transition to phase III. (After Hanfland *et al.*, ref. 4.)

gens of adjacent water molecules to which the molecule is linked by weaker hydrogen bonds. This combination of covalent and hydrogen bonding is also responsible for the rich variety of structures observed in ices—at least fourteen of which have been found, to date.[8]

Nearly 40 years ago, it was suggested that, at high density, when the distance between pairs of oxygen atoms is reduced sufficiently, hydrogen-bonded systems in general would form symmetric structures, with the hydrogens disposed midway between pairs of oxygens. Evidence for this long-sought form of ice has finally been obtained by infrared spectroscopy and x-ray diffraction at high pressure. Near the transition, the hydrogen atoms exhibit complex coupled motions, similar to those found in ferroelectric materials, as well as a quantum mechanical intermediate state characterized by proton tunneling. The new form of ice is stable to at least 210 GPa, where it has over four times the density of normal ice. Under these conditions, ice is no longer molecular but in fact forms an ionic crystal akin to the dense oxide minerals of the deep Earth. Shock-wave compression studies of the corresponding high-temperature fluid at high pressures reveal a marked increase in electrical conductivity, but with the carriers evidently being ions rather than electrons.[9] (Similar studies have been carried out on ammonia and other simple molecular systems.) Because water is a major component of the outer planets such as Uranus and Neptune, the findings are crucial for modeling the interiors and transport properties of those large bodies. Such modeling is required for a deeper understanding of the magnetic fields of these planets.[9]

Ice at low pressures is known to be orientationally disordered, but it can also be made into a positional glass. For centuries, a variety of glasses have been made by quickly quenching melts from very high temperatures. But high-pressure experiments have shown that high temperature is not always required. When normal ice (ice I) is compressed at liquid-nitrogen temperature, it transforms to an amorphous form with a density that is significantly higher than that of normal ice.[10] Further, when heated under ambient pressures, the quenched high-density amorphous ice transforms to a lower-density amorphous form—that is, a "phase transition" occurs between two amorphous states. Both phenomena—pressure-induced amorphization of crystals, and polyamorphism—have now been observed in a growing number of systems, including minerals, molecular solids and metals, and at both positive and negative pressures.[1] There is now evidence for a conjecture that the two "amorphs" of water ice are thermodynamically linked to two theorized fluid phases that merge at a critical point. The system would thus feature an unusual second critical point—that is, a critical point in addition to the common liquid/vapor critical point.[10]

New materials

At low density, simple closed-shell molecules and atoms interact weakly and at long range through van der Waals forces, as described above for xenon. They do not readily form stoichiometric compounds under normal conditions. However, recent experiments have shown that compounds can be made at high pressures, giving rise to a new class of materials, the so-called van der Waals compounds.[11] For example, nature's most inert atom, helium, and also its most stable simple molecule, N_2, combine to form a compound having the novel stoichiometry $He(N_2)_{11}$. A number of such compounds of this type, including $NeHe_2$,

$Ar(H_2)_2$, $(H_2)_4(O_2)_3$, $Ar(O_2)_3$ and several in the CH_4–H_2 system, have been observed at high pressures. Their crystal structures and stoichiometry can be understood in terms of the efficiency with which the molecules and atoms can be packed. Interestingly, these materials are isostructural with a very different class of materials across the great divide—namely, metallic alloys. Similar studies with H_2O have also led to the discovery of novel dense cage (clathrate) structures. Such high-pressure van der Waals compounds could form and condense in clouds of the dense atmospheres deep within the large planets, or as ices within their moons.

Technologically, silicon dioxide is one of the most important oxides known; it is the basis of isolation between active elements in transistor chips. Like H_2O, SiO_2 forms a tetrahedral network solid over a range of conditions, and as such its physical properties parallel in many ways those of ice. It also exhibits pressure-induced amorphization and densification in its glassy state.[1] Remarkably, despite the vast amount of work that has been done on silica over the years, new crystalline forms are still being reported, both in high-pressure experiments and in theoretical simulations.[12] These forms have important implications for the ceramic mantle of Earth's deep interior.

There is now great interest in the search for new high-strength ceramics.[13] The search includes testing predictions that phases of C_3N_4, starting with the hypothetical carbon analog of β-Si_3N_4, would be as incompressible as diamond, or even more incompressible. Meanwhile, recent breakthroughs in diamond technology include the use of ultrapure synthetic single crystals and the creation of anvils by chemical vapor deposition. The deposition technique can produce larger anvils and so-called designer anvils for the fabrication of microcircuits.[14]

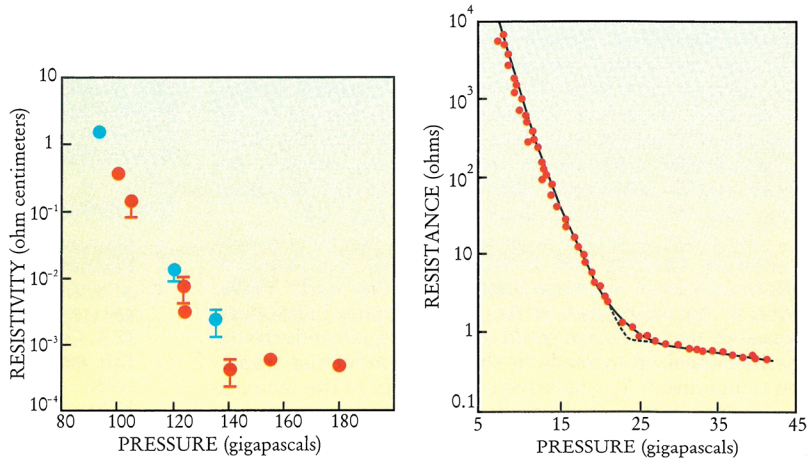


FIGURE 5. DECREASE IN RESISTIVITY due to pressure, for fluid hydrogen and solid iodine. **a:** Results of measurements made on hydrogen (red) and deuterium (blue). (From ref. 6.) **b:** The measured resistance drop in a sample of iodine upon static compression pinpoints its metallization (dashed line). (From Balchan *et al.*, ref. 3.)

Transforming metals and superconductors

Some 76 of the 92 naturally occurring elements are metals at one atmosphere, and more are made metals by the application of pressure. Bridgman's early electrical resistance measurements suggested that, under pressure, the simple alkali metals (the group I elements) might take on the characteristics of transition metals. This shift is the so-called $s \rightarrow d$ transition, a pressure-induced hybridization of the valence electrons in which states of d-character are brought down into the valence structure by pressure. Compression of metals causes changes in electronic structure that are intertwined with changes in crystal structure, electrical conductivity and bonding affinity. The alkalis and alkaline earth metals transform from formally d^0 to d^1 and d^2 metals; in effect, they assume the properties of other elements.

Evidence for chemical changes associated with these transitions has been documented by the synthesis of new potassium–transition metal compounds.[15] Potassium was recognized early on as a possible alloying element in Earth's core, in part because it was thought that its radioactive isotope could serve as a source of the planet's

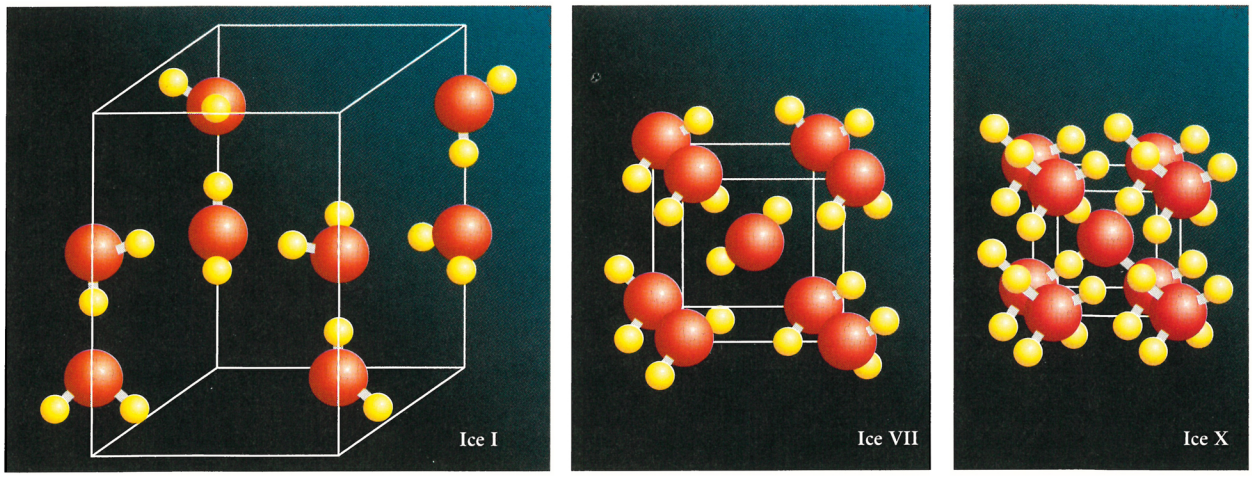


FIGURE 6. COMPRESSION OF ICE. Diagrams show the crystal structures of ice I (ordinary ice), ice VII and ice X. Ice VII forms at 2 GPa. The transition from ice VII to ice X begins at 60 GPa. Between 60 GPa and about 140 GPa, the system appears to undergo extensive quantum mechanical tunneling of protons. (Ice X structure proposed by W. Holzapfel, J. Chem. Phys. **56**, 712, 1972.)

internal energy. A potassium–iron alloy in the core is indeed a possibility. Recent studies of FeH, another possible core component, provide another example of pressure-induced chemistry in iron. (See PHYSICS TODAY, March 1998, page 17.) Pressure-induced changes in the elasticity of iron and such iron alloys are now the focus of considerable attention in relation to the recently observed elastic anisotropy and rotation of Earth's inner core. (See PHYSICS TODAY, August 1997, page 22.)

The effect of pressure on materials has been linked to another exciting and relatively recent phenomenon: high-temperature superconductivity. In the early 1960s, Alexei A. Abrikosov, now at Argonne National Laboratory, suggested that pressure could enhance superconductivity. The hypothesized increase in the superconducting transition temperature T_c was attributed mainly to the increase in average phonon frequencies with applied pressure or in high-pressure phases. This idea found partial expression in the subsequent calculations of high-temperature superconductivity in metallic hydrogen, cited above. Moreover, it was a consideration of the effects of pressure that played a prominent role in the search for higher-temperature cuprate superconductors in 1986 and the years following. Very high critical temperatures have been measured in mercury-bearing cuprates, with the highest T_c materials having a value of 135 K. Resistivity measurements of this material in a diamond cell revealed that T_c increases to 164 K at 30 GPa; this is currently the highest T_c on record.[16]

More recently, the study of pressure effects on superconductivity has been extended into an entirely new domain of pressure—the 100 GPa range—with striking results. Elemental sulfur is an even-valence, wide-bandgap insulator under normal pressures, but becomes metallic at about 90 GPa.[17] Measurements using new magnetic-susceptibility and electrical resistivity techniques with diamond cells have now shown[18] that sulfur transforms at this pressure not only to a metal, but also to a superconducting metal, with a transition temperature of 10.1 K. Moreover, T_c increases linearly with pressure up to 160 GPa, where, at the onset of a second structural phase transformation, it increases from 14 K to 17 K. These findings are particularly notable because highly compressed sulfur has the highest T_c's of any elemental solid measured to date, approaching twice that of niobium at one atmosphere. New high-pressure techniques thus not only provide a means for synthesizing new superconductors, but also provide unparalleled tests for theories of superconductivity through the precision with which they allow one to vary interatomic distances and perform physical measurements.

Future directions

Exploration of the pressure variable is increasing the number of known materials, and entirely new classes of materials are appearing as a result of pressure-induced changes in the chemistry of otherwise familiar elements. They include new dense polymers, semiconductor phases and even biomaterials, in addition to the materials outlined above. Novel physical phenomena may yet emerge with detailed study and the development of new techniques. For example, the use of newly built ultrabright synchrotron sources are making new classes of diffraction, spectroscopic and imaging experiments possible with high-pressure devices. The continued development of new electrical and magnetic techniques will be especially useful for exploring phenomena at ultralow (millikelvin) temperatures and 100 GPa pressures, currently uncharted territory. The important feedback between static and dynamic compression techniques is advancing high-pressure research as a new dimension, not just in condensed matter physics, but in physical science as a whole.

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