0 (zero momentum) axis in phase space. The corresponding dynamical tunneling (high-order Bragg scattering) time scale is on the order of a second, whereas the tunneling time scale associated with the original potential is 400 μs. Repeating the experiment for the pendulum reveals no oscillations on the faster time scale, showing that this possible direct mechanism is absent in the main experiment.

The authors also present some remarkable data at high temporal resolution where they identify an oscillation between the initial peak and the chaotic region near $p = 0$. This oscillation proceeds at a rate faster than the tunneling period and directly suggests the importance of a third chaotic state in mediating the tunneling between the islands.

Future studies need to examine the dynamics of a single atom, as distinct from the ensemble experiments that have so far been the norm. By combining laser cooling techniques with cavity quantum electrodynamics, researchers have monitored the motion of single atoms over time scales of dynamical importance (*12*). The theory of continuous quantum measurement applied to this experimental situation predicts (noisy) trajectories for the atom, and these predictions have turned out to be in good agreement with the measurement record (*12*). As these experiments improve, one can look forward to a fuller explication of yet another key problem, the actual appearance of classical chaos from the underlying quantum dynamics (*13*).

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Published online 5 July 2001;
10.1126/science.1062985.
Include this information when citing this paper.

PERSPECTIVES: SUPERCONDUCTIVITY

Super Boron

T. H. Geballe

Discovering new superconductors has been an important way of gaining insight into superconductivity ever since that spectacular macroscopic quantum state was discovered in Leiden almost a century ago. For the past 15 years, attention has focused on copper oxide materials (cuprates), but recent discoveries that MgB_2 and doped C_{60} are superconducting at unexpectedly high temperatures have moved the main group elements back into the limelight that they occupied in the early days of superconductivity. On page 272 of this issue, Eremets *et al.* (*1*) show that under high pressure, boron becomes superconducting. The result fills an important gap.

In the decades after World War II, main group and transition metals were found to behave very differently with respect to their superconducting properties. It turned out that the periodic table affords a natural basis for comparing superconductors and searching for new ones. It is not obvious that this should be so: The periodic table was developed from chemical behavior, where the energy scales are two or more orders of magnitude larger than superconducting energy scales. Nevertheless, clear patterns emerge (see the figure).

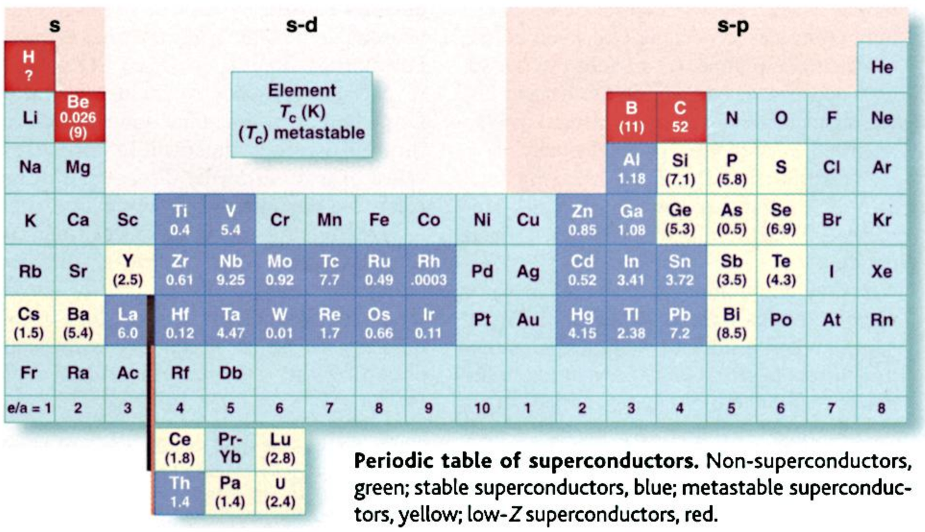
The value of the periodic table was recognized particularly by B. T. Matthias and co-workers. By noting the empirical trends, many new superconductors were discovered in the three decades after World War II. Far from being rare, superconductivity was found to be a commonly occurring ground state of nonmagnetic metals. During the same period, Bardeen, Cooper, and Schrieffer (BCS) discovered the microscopic pairing theory of superconductivity. BCS theory, although not successful in predicting new superconductors, was very successful in understanding and predicting the properties of known classes of superconductors (*2*).

A fruitful interaction between theory and experiment led a majority of scientists to believe that all superconductivity was due to a phonon-mediated electron pairing interaction. According to the simple BCS approximation, the transition temperature (T_c) is given by

$$T_c = 1.14\theta_d \exp - (1/NV) \qquad (1)$$

where θ_d is a representative average of the phonon energies involved in the coupling, N is the electron density of states at the Fermi level, and V is the electron-phonon scattering matrix. This equation is valid when the dimensionless electron-phonon coupling, NV, is small with respect to unity. It can be readily seen that for $NV < 0.3$, as is the case for light elements, one should not expect T_c's above 10 to 15 K, as is observed (see the figure). When the coupling becomes stronger, the BCS solutions involve more parameters as discussed by Eremets *et al.* (*1*). For the present purposes, however, the simple BCS approximation will suffice.

Eq. 1 captures the essence of why superconductors can be grouped according to their position in the periodic table. The light main group elements, from Be to S, become superconducting below ~10 K (with the exception of carbon, see below) if they are metallic or can be collapsed into a metallic phase by pressure or by quenching from the vapor. This can be understood in terms of their broad, featureless sp conduction bands and the weak



Periodic table of superconductors. Non-superconductors, green; stable superconductors, blue; metastable superconductors, yellow; low-Z superconductors, red.

The author is in the Department of Applied Physics, Stanford University, Stanford, CA 94305, USA. E-mail: geballe@stanford.edu

electron phonon coupling, which is expected from their good metallic conductivity. Heavy metals with sp conduction bands, such as Pb, Tl, and Hg, have strong electron phonon coupling constants but low Debye temperatures. In contrast, the superconductivity in transition metal alloys, such as Nb alloys, oscillates as a function of the number of electrons in the relatively narrow d bands. Their behavior can be understood in terms of the oscillating behavior of the density of states.

In spite of all the success, there was as of 1986 no theoretical reason why superconductivity should be limited to temperatures below the then seemingly impenetrable experimental limit of 23 K found in Nb_3Ge. Then, in 1986, Bednortz and Muller reported record high T_c's in copper oxide–based superconductors. The discovery sent shock waves through the physics community. Superconductors with T_c's above the liquid nitrogen temperature were soon discovered and could be prepared very simply.

The characteristics of this new family cannot be explained within the range of the usual BCS parameters. It is believed that the pairing is due to some novel mechanism(s). There are plenty of candidate mechanisms but no consensus as yet as to which is correct. A record T_c above 150 K (*3*) for $HgBa_2Ca_2Cu_3O_{8-x}$ under pressure has been reached, but no further increases have been reported in the past 8 years.

Still, the quest for room temperature superconductors remains alive. Recently, two new superconductors have been discovered whose T_c's far exceed all known noncuprate superconductors. C_{60} doped with electrons by charge transfer from intercalated alkali metals or by field-effect charge transfer has a T_c of up to 40 K and 52 K, respectively (*4*, *5*), and MgB_2 reaches 39 K (*6*)—well above the previous record of 23 K. Both systems are composed of light, low-*Z*, main group elements. Their high T_c's are most likely associated with a large preexponential factor in Eq. 1 due to modes associated with vibrations of these light atoms, which couple effectively to the conduction electrons. Less likely, but not yet excluded, is a second pairing mechanism that can supplement the phonon-mediated mechanism and enhance the superconductivity.

The fact that the T_c of MgB_2 is well above the T_c's of the other light elements—in fact, well above all known superconductors before 1986 (see the figure)—raises the question of whether there is some novel physics special to the pairing in MgB_2. When Akimitsu, the principal author of (*6*), was asked to explain what led to the discovery of the high T_c, he replied "It's a long story." It is not clear whether the long story involves simply testing a compound that easily could have been tested a generation ago (*7*), whether the discovery followed from an inspirational recognition of the structural relationship of the graphite-like boron layers intercalated with Mg to that of isoelectronic graphite intercalated with alkali metals (*8*), or whether it involved some as yet undisclosed insight.

MgB_2 raises the interesting question of how elemental boron itself will behave, provided that it can be collapsed into a metallic phase. Eremets *et al.* have answered this question in a beautiful set of experiments, which enabled them to carry out electrical measurements on a flake of boron under high pressures. At atmospheric pressure, boron is a semiconductor with an open structure composed of tightly bonded B_{12} icosahedra, which are linked into three-dimensional open structures. Eremets *et al.* find that boron becomes metallic at about 160 GPa at room temperature. The metallic phase becomes superconducting at 6 K. Further increases in pressure up to 250 GPa raise the T_c to 11.2 K.

The structure of the dense metallic boron phase is as yet unknown, but there is no indication of unusual pairing mechanisms as might arise if bonding remained molecular in the metallic phase (as is the case in metallic molecular hydrogen) (*9*). The order-of-magnitude increase in T_c of boron over aluminium is within the range of behavior expected from Eq. 1 and may be attributed to the higher vibrational frequencies in boron without invoking any novel mechanism. The only unusual behavior of superconducting boron is the sign and size of the pressure coefficient of T_c.

The Holy Grail of the low-*Z*, high-pressure approach to superconductivity remains metallic hydrogen. Model estimates (*10*) suggest that hydrogen may become a molecular metal at 400 GPa with a T_c as high as room temperature. In the model, the pairing interaction is mediated by high-frequency phonons in combination with molecular excitations. Although Eremets *et al.* have not found enhanced unusual superconductivity in the new metallic phase of boron, they have succeeded in preparing the metallic phase for the first time and have added to the long story on the road to room temperature superconductivity. Perhaps the gap they have filled will inspire someone to write the concluding chapter.

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PERSPECTIVES: NEUROSCIENCE

Parkin and Its Substrates

Christian Haass and Philipp J. Kahle

Parkinson's disease (PD) has long been considered a textbook example of a sporadic neurodegenerative disorder. Patients with PD have characteristic motor deficits caused by loss of dopaminergic neurons in the brain's nigrostriatal pathway. Postmortem brain tissue from PD patients reveals the presence of inclusions called Lewy bodies in dopaminergic neurons, although whether these inclusions are a cause or a result of the disease is still unclear (see the figure). The discovery several years ago of gene mutations causing rare familial forms of PD provided the first molecular glimpse of a reason for the selective dopaminergic neuronal loss in this disorder. Missense mutations in the gene encoding the α-synuclein protein were found in families with an inherited autosomal-dominant form of PD (*1*, *2*). Various mutations in the *PARKIN* gene were discovered in families with a rare autosomal-recessive juvenile form of parkinsonism (AR-JP) (*3*, *4*). It is generally believed that the two familial forms of PD are not connected, and so research on α-synuclein and parkin has proceeded separately. This arrangement, however, is set to change with the article by Shimura and colleagues (*5*) on page 263 of this issue. Knowing that parkin is an E3 ubiquitin ligase and speculating that parkin and α-synuclein might interact, these investigators now provide provocative evidence that parkin regulates the degradation of an unusual form of α-synuclein through the attachment of ubiquitin. The covalent attachment of ubiquitin to a protein by an E3 ubiquitin ligase (ubiquitination) targets that protein for destruction in the cell's garbage dump, the proteasome (*6*). The fact that α-synuclein

The authors are in the Laboratory for Alzheimer's and Parkinson's Disease Research, Department of Biochemistry, Ludwig Maximilians University, 80336 Munich, Germany.