New Conventional Superconductor Found with a Surprisingly High T_c

The setting was a symposium on transition metal oxides in Sendai, Japan. The date, 10 January. Somehow, a rumor had spread that Jun Akimitsu of Tokyo's Aoyama-Gakuin University would announce the discovery of a room-temperature superconductor. Instead, and with a touch of apology, Akimitsu described a new superconductor, magnesium diboride (MgB_2), whose 39-K critical temperature T_c is more medium than high.[1]

Despite the modest T_c, Akimitsu's discovery has touched off a burst of research activity worldwide. More than 40 preprints about the new superconductor have been posted on the Los Alamos preprint server. Why the fuss?

Unlike the devilishly complex high-T_c cuprate ceramics, MgB_2 appears to be a conventional superconductor of the sort whose theoretical basis was outlined decades ago by John Bardeen, Leon Cooper, and Robert Schrieffer (BCS). Theoretical tractability is not the only advantage MgB_2 has over the cuprates. Experiments carried out by David Larbalestier and others at the University of Wisconsin—Madison and Doug Finnemore and others at Iowa State University indicate that MgB_2's grain boundaries don't stifle current flow.[2] Moreoever, the 39-K T_c comes straight off the rack. Tailoring MgB_2's material properties could send T_c higher.

Akimitsu published his discovery in the 1 March issue of *Nature*, but the first MgB_2 preprint appeared on the Los Alamos server on 31 January, just three weeks after the Sendai symposium. In that early paper, Paul Canfield's group at Iowa State University explained how to make pure samples of MgB_2 and measured the compound's isotope effect.[3]

In conventional superconductors, lattice vibrations (phonons) push electrons into pairs, which form a superconducting condensate. Lighter isotopes lead to higher phonon frequencies, which, in turn, lead to higher transition temperatures. This isotope effect is absent in high-T_c cuprates, whose superconductivity depends on subtle, phonon-free coupling between electrons.

> Magnesium diboride, a black powdery material you can buy off the shelf for less than \$2 a gram, turns out to be a superconductor.

By finding a large isotope effect, Canfield and company confirmed the key role of electron–phonon coupling in MgB_2. A host of subsequent measurements by other groups have further elucidated MgB_2's normal and superconducting states. Just above T_c, its resistivity is about 75 $\mu\Omega$ cm, which is lower than many simple metals. And H_{c2}, the value of the applied magnetic field that destroys the superconducting state, is about 16 T at 0 K.

But MgB_2's life as a superconductor began a mere two months ago, so it's perhaps not surprising that some measurements reported so far disagree. Estimates of the size of the superconducting gap, for example, range from 2 to 7 meV. And although most experiments point to MgB_2 being a conventional *s*-wave BCS superconductor, some see possible evidence of unconventional behavior.

BCS revisited

Before the coming of the high-T_c cuprates in the mid-1980s, researchers looked to BCS theory to guide them toward higher T_c. As refined in the 1960s by Guerassim Eliashberg, Arkadii Migdal, Bill McMillan, and others, BCS theory gives T_c in terms of the Debye temperature Θ_D, which is proportional to the characteristic phonon frequency of the lattice, and two dimensionless constants, λ (the coupling constant) and μ^* (the Coulomb pseudopotential):

$$T_c = \frac{\Theta_D}{1.45}\exp\left[-\frac{1.04(1+\lambda)}{\lambda-\mu^*(1+0.62\lambda)}\right]$$

At first glance, the path to higher T_c lies in the direction of higher Θ_D. For most elements, Θ_D is around a few hundred K, but for some light elements that form strong covalent bonds, in stiff lattices, Θ_D can be much higher. Diamond has a Θ_D of 2250 K; boron's is 1480 K. But a high Debye temperature can also lower T_c. That's because the coupling constant λ can decrease if the phonon frequencies are large.

Neither carbon nor boron is a superconductor under normal conditions, so each must be combined with other elements. And there lies a potential problem: If you form a compound with boron or carbon and a metal, you can't guarantee that the coupling phonons will come from the light element and not from the metal.

That doesn't seem to be the case with MgB_2. Groups from the Naval Research Laboratory (NRL) in Washington, DC,[4] the University of California, Davis,[5] and the Max Planck Institute for Solid State Research in Stuttgart[6] have independently calculated the material's electronic band structure. And, though they don't all focus on the same details, they have formed a consistent picture of MgB_2's superconductivity.

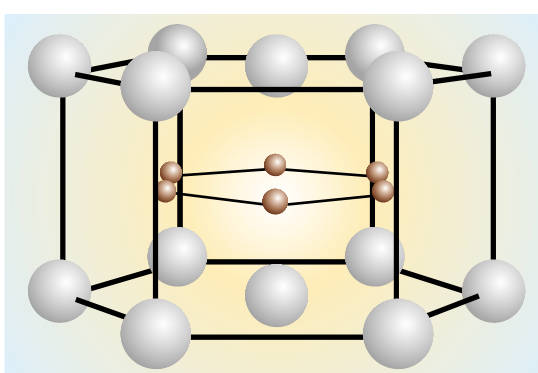

FIGURE 1. MAGNESIUM DIBORIDE belongs to the AlB_2 family of structures. The magnesium atoms, shown here in gray, form a hexagonal layer, while the boron atoms, shown in brown, from a graphite-like honeycomb layer.

The two key BCS ingredients, charge carriers (holes and electrons in the case of MgB_2) and phonons, come from the boron atoms. But there's a twist: One group of phonons contributes to the superconductivity far more than all the others. These phonons, explains NRL's Igor Mazin, originate in a vibrational mode that corresponds to the contortion of the boron layer (figure 1). The mode couples to an electronic state, the σ state, formed by the in-plane boron p orbitals.

Although they contribute neither phonons nor charge carriers to the BCS coupling, the magnesium atoms play a key role. By donating their two valence electrons to the boron atoms, the magnesium atoms become positively charged and attract electrons. Feeling the strongest attraction are the electrons in the out-of-plane boron p orbitals, which constitute the boron π state. As a result of the attraction, the energy of the π-state electrons is lowered. "And that," says UC Davis's Warren Pickett, "is what causes the hole-doping of the σ bands. The attraction lowers the energy of the π bands enough to accept electrons from the σ bands."

Those holes can be filled by electron doping. Working in Bob Cava's lab at Princeton University, Joanna Slusky and others investigated the effect of substituting the magnesium with aluminum, which has one more valence electron. At an aluminum content of 10% and higher, superconductivity is suppressed. The Princeton team also found that adding aluminum causes the boron interplane distance to shrink discontinuously. Between aluminum contents of 10% and 25%, a new, more tightly layered phase coexists with the phase that superconducts. Above 25%, the superconducting phase disappears.

That MgB_2 is on the brink of a structural instability could be helpful to its superconductivity. Phase transitions can supply low-energy phonons that boost the electron–phonon coupling. The proximity of the structural phase transition might also explain why superconductivity isn't found in the other metal diborides: Only magnesium has the right combination of size and charge distribution to turn boron into a superconductor.

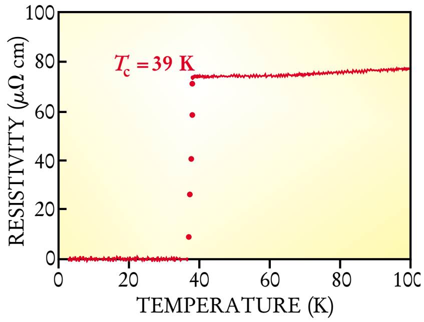

FIGURE 2. SUPERCONDUCTIVITY in magnesium diboride appears at a temperature of 39 K. (Adapted from ref. 1).

Overlooked

Condensed matter physicists are amazed that MgB_2's superconductivity went undiscovered for so long. Walther Meissner found several superconducting interstitial compounds of transition metals with borides, carbides, and nitrides in Berlin in the 1930s. Two decades later, John Hulm and Bernd Matthias discovered more superconducting borides—with transition metals—at the University of Chicago. But how did they miss MgB_2?

Stanford's Ted Geballe, who began working on superconductors in the 1950s, speculates that the procedures Hulm and Matthias used probably failed for nontransition elements such as magnesium because they would have made an insulating oxide. Florida State's Zack Fisk offers an alternative explanation. He points out that Matthias made his compounds in an arc furnace. If magnesium isn't confined under pressure (hard to do in an arc furnace), it evaporates long before it reaches boron's rather high melting temperature.

Clearly, as figure 2 shows, Akimitsu didn't miss MgB_2's superconductivity—but not because he was deliberately looking for it. Hoping to find a new superconducting system, he and his team were investigating ternary compounds of magnesium, boron, plus a transition metal, such as titanium or vanadium. As they reduced the proportion of magnetic atoms, they found that the compounds' superconducting properties improved, with the best performance coming from the compound that completely lacked transition metal ions.

It's too early to say whether materials based on MgB_2 will be technologically useful. But one step in that direction has already been taken. The Iowa State group has made dense superconducting wires out of the compound.[7]

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Have We Glimpsed 'New Physics' in the Muon's Anomalous Magnetic Moment?

A $g - 2$ measurement at Brookhaven's muon storage ring shows a small but tantalizing disagreement with the standard model.

The anomalous magnetic moments of the electron and its heavier sibling, the muon, can be measured with exquisite precision. And they are unique probes of fundamental physics. The electron's anomalous magnetic moment (a_e), known to 4 parts per billion, provides by far the best determination we have of the fine-structure constant α. (See PHYSICS TODAY, March 2001, page 29.) The muon's anomalous magnetic moment (a_μ), though not quite so spectacularly measured, is in fact a more sensitive probe of putative "new physics" beyond the standard model of elementary particle interactions. That's essentially because m_μ, the mass of the muon, is about 200 times the electron's mass.

Hence the cautious excitement in February, when the international Muon ($g - 2$) Collaboration announced the latest results from its experiment (see figure 1) at the Brookhaven National Laboratory. The completed analysis of its 1999 data, the group reported, had shrunk the uncertainty of its a_μ measurement enough to show a tantalizing but still tentative disagreement with the standard-model prediction.[1] At this point, the measured a_μ, with an uncertainty of 1.3 parts per million, is 2.6 standard deviations larger than the calculated theoretical value.[2]

Is this a harbinger of new physics? "We'll know better when the analysis of our 2000 and 2001 data has brought our experimental error down by about another factor of 3," says collaboration co-spokesman Lee Roberts (Boston University). The other spokesman is Vernon Hughes (Yale), who set this ambitious undertaking in motion