Cuprate Superconductors: A Broken Symmetry in Search of a Mechanism

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The discovery of high-temperature cuprate superconductors in 1986 took every condensed-matter physicist by surprise. These materials are distinctly different from previously known superconductors in at least two respects. First, above the superconducting transition temperature, they are unusual metals. They do not seem to fit the paradigm of the Landau Fermi-liquid theory that has served us well over the past 40 years. In this theory, the low-energy excitations that determine the macroscopic properties of metals at low temperatures are like bare electrons, with modest changes in their attributes owing to electron-electron interaction. We can now explain why, in a metal like copper, interacting electrons behave effectively like free electrons. Thus, our ability to predict the properties of complex solids has increased. The new materials, however, seem to require new principles.

The second distinguishing feature of these materials is the high value of the superconducting transition temperature—as high as 150 K under pressure (*1*) and 135 K at the ambient atmospheric pressure (*2*): Perhaps materials that superconduct at room temperatures (300 K) will be found in the near future. A tantalizing empirical fact in this respect is that the transition temperature increases systematically with the number of copper-oxygen layers in the building blocks of these materials; the unit cells of the crystal lattice.

If we recall that considerable systematic effort never led to transition temperatures higher than 23.2 K (Nb_3Ge) in the conventional materials, it is plain that the underlying microscopic mechanism in the new materials is different. The search for the mechanism has therefore become one of the central problems in condensed-matter physics. Where should we then look?

Physicists are enamored of symmetries and symmetry principles. Such general principles allow them to restrict possible theories. A lively topic that is currently debated, both experimentally and theoretically, is the symmetry of the quantum mechanical wave function of the superconducting state. Unfortunately, there are good reasons to believe that the constraints implied by the symmetry of the wave function may not be sufficiently strong to unravel the mechanism in the sense in which we would like to understand it, and it is the mechanism that sets the high transition temperatures in these materials.

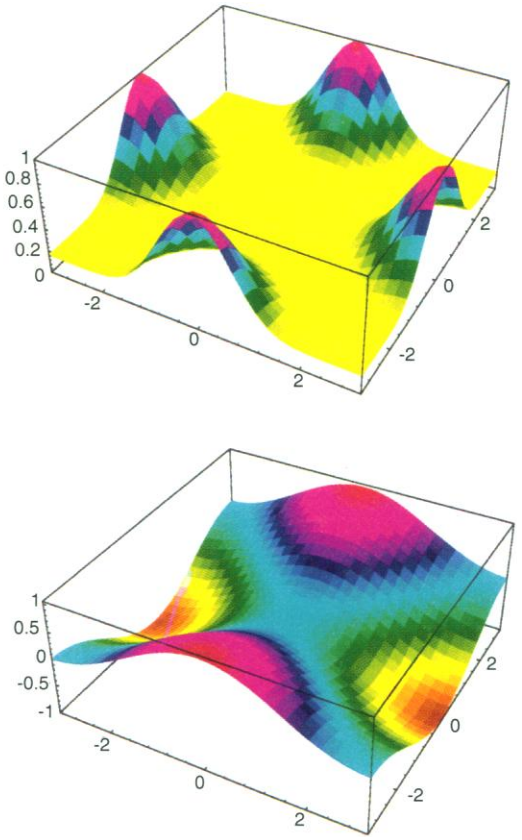
There is little doubt that the superconducting state in the high-temperature superconductors is characterized by spontaneously broken symmetry as in the original theory of superconductivity of Bardeen, Cooper, and Schrieffer (BCS), a fact that was not clear in the beginning. In this sense, these materials are well understood. There are two distinct aspects of the BCS theory, however: The first identifies the onset of superconductivity with an unusual broken symmetry and predicts a very specific phenomenology based on this fact alone, and the second identifies the cause, or the mechanism, of the broken symmetry. These issues are quite distinct.

The phenomenon of spontaneously broken symmetry is common in condensed-matter systems. It is often found that even though the microscopic specifications of a system (technically defined by the Hamiltonian) satisfy certain symmetries, the state of the matter does not. For example, the microscopic specifications of a liquid above the freezing temperature are the same as those of the crystalline solid and satisfy the symmetry of full translational invariance. Nonetheless, the periodic arrangement of the solid respects only a restricted set of translational symmetries—the symmetries with respect to displacements by the multiples of the lattice spacing and not with respect to any arbitrary displacement. The solid in the broken symmetry phase is more ordered, and the measure of the order can be formulated in terms of an order parameter, which is an additional macroscopic variable.

The symmetry that is spontaneously broken in a superconductor is more subtle because it is inherently quantum mechanical. It is the symmetry with respect to the global change of the phase of the quantum field operators representing individual electrons. The superconducting order is quantified in terms of an order parameter, having both a magnitude and a phase, called the gap. The superconducting gap is also directly related to the wave function of an electron pair, the Cooper pair, and the superconducting state is a state in which the electrons are correlated in pairs.

The recent excitement in the area of high-temperature superconductors concerns the anisotropy and the symmetry of this order parameter, the superconducting gap. The anisotropy has been explored by angle-resolved photoemission spectroscopy (*3*) and the symmetry by phase-sensitive Josephson measurements (*4*). It is fair to say that a consensus has not yet been reached.

The mechanism that causes superconductivity in conventional materials is the attractive force between the electrons that arises from the exchange of phonons, the quanta of lattice vibrations. In other words, lattice distortion mediates the pairing. This could not be all because the electrons repel each other because of Coulomb interac-



Superconductor symmetries. Two representative superconducting gaps, whose magnitudes are normalized to their maximum values, are plotted within the first Brillouin zone as a function of the wave vectors k_x and k_y, in units of the inverse lattice spacing of the square-planar CuO planes. The gaps are depicted to be highly anisotropic, unlike those in conventional superconductors. The top panel is the anisotropic *s*-wave gap, which has the fourfold symmetry of the square lattice as we rotate about the center. It does not change sign, and although small, it does not vanish along the diagonals. The bottom panel is the *d*-wave [more precisely, $d_{(x^2-y^2)}$] gap that has only two-fold rotational symmetry about the center and vanishes along the diagonals, changing sign as we go around the center. The fourfold symmetry can be restored if we agree to change the sign as we rotate by 90 degrees.

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tion. Indeed, a simple calculation shows that the Coulomb repulsion and the phonon-mediated attraction roughly cancel each other. How do the electrons evade Coulomb repulsion in this mechanism? It turns out that the Coulomb repulsion gets screened (that is, the range of the interaction is decreased), and thus its effect on the electrons is much reduced, on a time scale far shorter than the time scale on which phonon-mediated attraction operates.

Consider magnetism as an example of why it is so difficult to infer mechanism from macroscopic measurements. We now know that the dominant mechanism of magnetism in solids is electrostatic interaction combined with the Pauli exclusion principle, known as the exchange interaction. We also know that this mechanism is rotationally symmetric. It only depends on the relative orientation of the electronic spin angular momenta and not on their orientation with respect to the crystal lattice. A complex set of weaker interactions that are due to the magnetic dipolar interaction, spin-orbit coupling, and crystalline electric fields break the symmetry (as opposed to the spontaneously broken symmetry discussed above) with respect to rotations of the spin coordinates. Although magnets with extremely high magnetic transition temperatures, such as iron, were known to the Phoenician sailors, or even earlier, the understanding of the mechanism is a 20th-century post–quantum-mechanical achievement. In other words, a major revolution in physics was necessary in order to understand the mechanism of magnetism. Do we need at least a minor revolution before we can understand the mechanism of superconductivity in high-temperature superconductors? I think the answer is yes.

Imagine that we knew nothing about the origin of magnetism but could perform very sophisticated measurements involving the excitation spectrum and the magnetic transition temperatures; for simplicity, it is enough to consider insulating magnets. First, we would quickly discover that there are magnets with a wide range of transition temperatures, from 1 mK to 1000 K. We may even discover that low-dimensional magnets have transition temperatures that are considerably lower than those of three-dimensional magnets, and we could understand this difference in terms of large fluctuation effects destroying order in low-dimensional systems. We could consider this to be a victory, and if we were to design a magnet with a high transition temperature, we would choose one that is three-dimensional.

With hindsight, does this bring us closer to the mechanism of magnetism in solids? I think not. Consider this magnet analogy further. Suppose that sophisticated experiments revealed that the elementary excitations in one class of magnets exhibit an energy gap in the spectrum. Let us define them to be the "Ising magnets." Suppose, also, that the same measurements revealed that there is another class of magnets, defined to be the "Heisenberg magnets," whose elementary excitation spectrum is a continuum without a gap or spin waves. Does this imply that the mechanism is fundamentally different for these classes of materials? The answer is no. With hindsight, we know why these two materials are so different. In both cases, the dominant mechanism is the exchange interaction, but the smaller anisotropic interactions are different. In the disordered phase, the small difference in anisotropies is difficult to discover, but in the ordered phase, the small difference is amplified because of long-ranged macroscopic correlations, a cooperative effect. To summarize this argument, the distinctly different elementary excitation spectrum is not necessarily simply related to the mechanism; in this case, the exchange interaction.

This leaves us little choice but to adopt a reductionist approach and begin with the chemistry of these materials. My feeling is that we may not have to go back too far. There are already some interesting clues. These materials have nearly universal but unusual normal state properties, whereas their superconducting properties are unusually varied (*5*). Could this be due to small microscopic differences, like the anisotropy energies in a magnet, that are magnified in the ordered phase? If we are to take the magnet analogy seriously, we must conclude that the fundamental mechanism is most likely unique but that smaller microscopic differences are in the way.

References and Notes

1. C. W. Chu *et al.*, *Nature* **365**, 323 (1993).
2. A. Schilling *et al.*, *ibid.* **363**, 56 (1993); L. Gao *et al.*, *Physica C* **213**, 261 (1993).
3. Z.-X. Shen *et al.*, *Phys. Rev. Lett.* **70**, 1553 (1993).
4. D. Wollman *et al.*, *ibid.* **71**, 2134 (1993); P. C. Chaudhuri and S.-Y. Lin, *ibid.* **72**, 1084 (1994); A. G. Sun *et al.*, *ibid.*, p. 2267; C. C. Tsuei *et al.*, *ibid.* **73**, 593 (1994).
5. P. W. Anderson, *Science* **256**, 1526 (1992).
6. I acknowledge interesting conversations with A. Ruckenstein and J. Rudnick and thank the Aspen Center for Physics for their hospitality. This work was supported by the National Science Foundation, grant number NSF-DMR-92-20416.

Chromosome End Games

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The linear chromosomes typical of higher organisms have an obvious feature not found in circular bacterial chromosomes: They have ends. The DNA double helix in the chromosome interior is replicated by DNA polymerase. The polymerase does not start DNA chains de novo, but always reaches to one side and extends the end of a preexisting primer strand bound to the template. Such an enzyme is frustrated at the chromosomal end, or telomere. If you are already at the end of a line and reach outward, there is nothing there to extend. The solution to this problem is telomerase, a telomere-extending enzyme that until recently had been subject to molecular analysis only in ciliated protozoa. This situation has now changed with discoveries of telomerase enzymes in yeast cells, one of which is reported in this issue of *Science* (*1*).

Telomerase was first described a decade ago by Carol Greider and Elizabeth Blackburn in *Tetrahymena*, a single-celled pond organism with an unusually large number of nuclear DNA molecules and therefore many telomeres (*2*). Telomerase is not the usual protein enzyme but is instead a ribonucleoprotein. Its RNA subunit includes a 5'-CAACCC-3' sequence that serves as template for the addition of 5'-GGGTTG-3' repeats to chromosome ends (*3*) (see figure).

As in *Tetrahymena*, most other eukaryotic chromosomes terminate in repeats of a short DNA sequence with one strand rich in G (guanine) bases, so it seemed likely that telomerase would be key to telomere replication in general. Indeed, the *Tetrahymena* telomerase served as the springboard for cloning and sequencing the telomerase RNA subunits from a number of other ciliated protozoa (*4*). But the RNA turned out to have a fast evolutionary clock: Outside the template region its sequence diverged rapidly from species to species. Thus, although the activity of the enzyme could be detected in diverse cells, including human cells (*5*), isolation of any molecular component of telomerase remained restricted to the ciliated protozoa.

The announcement by Singer and Gottschling of the finding of the gene for telomerase RNA in the yeast *Saccharomyces cerevisiae* (*1*), a tractable system for genetic manipulation, has therefore been enthusi-

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