continually switching a single receiver between two identical horn antennae pointing in different directions. The radiometers sweep the sky as the spacecraft spins on its axis and its near-polar orbit stays close to the Earth's twilight zone.

If it turns out that the cosmological quadrupole moment is much larger, relative to the higher moments, than is required by the standard inflationary model, one will have to think of more exotic explanations: Perhaps the universe as a whole is spinning, or the general expansion is not isotropic. "There are perfectly good models for a nonisotropic Big Bang," Wright told us. "The only way to discard them is with the COBE data." At the Washington AAS meeting Smoot pointed out that the early DMR data already put an upper limit on the cosmic quadrupole moment that translates into a reassuring limit on how fast the universe might be spinning. "If it is spinning," he said, " it seems to have completed less than a thousandth of a turn since the Big Bang."

—Bertram Schwarzschild

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# DO OXIDE SUPERCONDUCTORS BEHAVE AS FERMI LIQUIDS?

When a photon knocks an electron out of a material, the freed electron reveals some secrets about the electronic environment it left behind. Such clues are sought by theorists puzzling over the mechanisms for high-temperature superconductivity, but high-resolution data have only become available in the past year. The behavior they reveal resembles the familiar patterns of conventional superconductors in the normal states—but with subtle and complex deviations that are now the focus of intense theoretical attention. The data have confirmed earlier measurements of a superconducting gap and provided direct evidence for a Fermi edge in momentum space.

Traditionally, photoemission measurements, which are very useful for studying metals, insulators and semiconductors, have not been applied to conventional superconductors because these methods do not have sufficiently fine energy resolution to probe the energy region of greatest interest in a superconductor—the narrow forbidden-energy gap that opens as electrons near the Fermi surface pair up at slightly lower energy in the superconducting state. According to the BCS theory, which has been so successful in describing conventional superconductors, the size of the superconductivity gap depends on the critical temperature. Thus if the same mechanism is responsible for the superconductivity in the oxide materials, whose critical temperatures are about ten times higher, the superconductivity gap is expected to be within the reach of photoemission experiments.

Furthermore photoemission offers a unique opportunity to probe the behavior of the Fermi surface both above and below the critical temperature. Not only are such experiments of renewed interest, but recent improvements in sample preparation and increases in angular and energy resolution have given these techniques the required sensitivity.

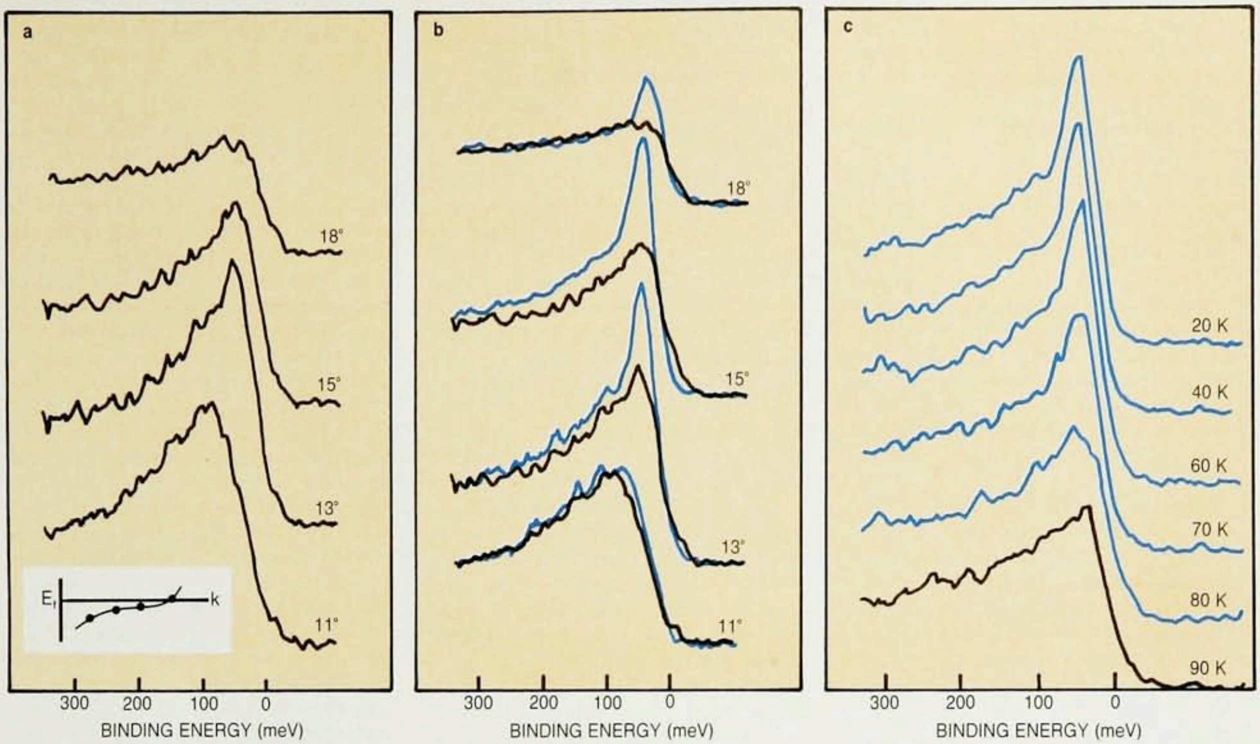
### Normal-state behavior

Angle-resolved photoemission data are uniquely qualified to answer the question of whether the oxide materials behave as Fermi liquids in their normal state. As described by Lev Landau, a Fermi liquid is a system of weakly interacting particles, known as quasiparticles, whose behavior is qualitatively similar to that of a system of noninteracting fermions. The Fermi liquid has formed the conceptual framework for understanding the behavior of the low-temperature superconductors above their critical temperatures. Although there is no *a priori* reason why the oxide superconductors should act as Fermi liquids, many researchers have tended to compare the observed behavior to this standard. It serves for them as a starting point from which they might extend the theory to explain high-temperature superconductivity. Others have nearly completely scrapped this viewpoint and have proposed new mechanisms of interaction that depart radically from the BCS theory. One such approach is the resonating-valence-bond theory, which envisions that the departure of the electron creates not a hole but two entities—a chargeless "spinon" and a spinless, charged "holon."

In Fermi liquids the locus of points in **k** space defines a Fermi surface (**k** is the lattice wavevector for zero-energy single-particle excitations). All electrons in the system must be accommodated within the volume of this surface in momentum space. If quasiparticles exist, they should give rise to a peak in the energy spectrum, with that peak growing more narrow as **k** approaches the Fermi momentum. Beyond the Fermi energy the peak should disappear. By measuring the energy spectrum for different photoelectron emission angles researchers can essentially probe different regions of **k** space and determine whether the quasiparticle peak exists and how it behaves as the Fermi momentum is approached.

In photoemission studies, the incoming photon gives essentially all its energy to a single electron, which is assumed not to have appreciable interactions as it leaves the crystal. The momentum of the photon is negligible, so that the electron that emerges has momentum nearly opposite to that of electrons remaining behind in the sample. The most energetic electrons ejected come from the Fermi surface. To locate the position of the Fermi surface the experimenters first measure the energy spectrum of a normal metal. Then, with the same initial value of photon energy, they measure the energy spectrum at selected emission angles. Three groups have published angle-resolved photoemission spectra, all on the compound $Bi_2Sr_2CaCu_2O_8$, for which it is easy to prepare high-quality, chemically stable single-crystalline surfaces.

The figure on page 21 shows the energy distribution reported by an experiment[1] that has simultaneously both high angular and energy resolution (30 meV). It was performed at the Synchrotron Radiation Center of the University of Wisconsin by a collaboration consisting of Clifford Olson, Rong Liu, An-Ban Yang and David Lynch (Iowa State University), Scott List and Al Arko (Los Alamos National Laboratory) and Boyd Veal, Ying Chuan Chang, Pei-Zhi Jiang and Paul Paulikas (Argonne National Laboratory). Similar results[2] with better angular resolution and somewhat lower energy resolution were obtained by group working at HASYLAB in Hamburg, West Germany. The researchers there are Recardo Manzke, T. Buslaps and R. Claessen (University




**Behavior of high-temperature superconductors** seen in angle-resolved photoemission studies on $Bi_2Sr_2CaCu_2O_8$ with 22-meV incoming photons. **a:** Energy spectrum of electrons ejected from the normal state at 90 K reveals a strength near the Fermi energy (0 meV binding energy) that grows as the momentum **k**, determined by the angle of the outgoing electron, approaches the Fermi surface calculated from conventional band theory (see inset). However, the width of the peak just below the Fermi energy does not behave entirely as expected for a Fermi liquid. **b:** Comparison of energy distributions above and below the critical temperature gives evidence that a superconductivity gap has developed at the Fermi energy, depleting the intensity above that energy and increasing it below. Black curves are at 90 K and blue ones at 20 K. **c:** Energy distributions at an emission angle of 15° as a function of temperature show that the gap is related to the superconductivity transition at 82 K. (Adapted from ref. 1.)

of Kiel) and Jorg Fink (KFA, Karlsruhe, West Germany).

Still more data, with lower resolution,[3] were reported by a Japanese research group consisting of T. Takahashi, H. Matsuyama, H. Katayama-Yoshida, Y. Okabe and S. Hosoya (Tohoku University), K. Seki (Hiroshima University) and H. Fujimoto, M. Sato and H. Inokuchi (Institute for Molecular Science, Okazaki).

The left-hand part of the figure shows the energy spectrum of the oxide above its critical temperature at an initial photon energy of 22 eV for four different angles, corresponding to four different directions in **k** space. In their paper, Olson and his colleagues note that there is very little strength at the Fermi surface in the 11° data, but that the strength grows with increasing angle until, at 18°, the density of states appears filled up to the Fermi level. Band calculations indicate that the band crosses the Fermi level at about 18°, a result that the experimenters feel is consistent with their interpretation. Although many agree that the foregoing behavior is what one expects of a Fermi liquid, the data suggest an important departure: The lifetime broadening, as indicated by the width of the peak, varies linearly with $E - E_f$, whereas the Fermi liquid picture requires the width to go as $(E - E_f)^2$.

## Superconductivity gap

The photoemission data in figure b can be used to determine the superconductivity gap. The energy distribution at 20 K, far below the material's critical temperature of 82 K, is shown superimposed at each of four angles on the corresponding distribution at 90 K. In each case, the salient change as the material goes below its critical temperature is a decrease in the density of states at the Fermi energy and an increase in the density of states just below the Fermi energy. This shift corresponds to the opening of the forbidden gap in the superconductor. Researchers determine the width of the gap by fitting the spectra with a combination of a linear background and a Lorentzian shape modified by the BCS density of states for the low-temperature data.

The earliest attempts to measure the superconductivity gap with photoemission were inconclusive, but just over a year ago photoemission studies yielded estimates for the superconductivity gap in $Bi_2Sr_2CaCu_2O_8$ crystals. One of these was a photoemission experiment[4] with high-energy resolution (20 meV) done by the collaboration of Jean-Michel Imer, Francois Patthey, Boris Dardel, Wolf-Dieter Schneider and Yves Baer (University of Neuchatel, Switzerland), Yves Petroff (University of Paris, South) and Alex Zettl (Lawrence Berkeley Laboratory). Another group, doing an experiment with lower energy resolution (150 meV), also reported evidence for a superconductivity gap. This group consisted of Yeh Chang, Ming Tang, Roberto Zanoni, Marshall Onellion, Robert Joynt, David Huber and Giorgio Margaritondo (all of the physics department and the Synchrotron Radiation Center at the University of Wisconsin) and Pat Morris, William Bonner, Jean-Marie Tarascon and

Ned Stoffel (Bellcore).[5] Fink and his collaborators measured a superconductivity gap at about the same time. All these experimenters determined a gap width on either side of the Fermi surface of about 30 meV, corresponding to a full superconductivity gap of 8 k $T_c$. This value is about twice the size 3.52 k $T_c$ predicted by BCS theory.

Recently Olson and his Ames–Los Alamos–Argonne collaborators reported new angle-resolved photoemission data that indicate that the gap value remains constant at about 24 meV, independent of the direction in **k** space within the basal plane. This result implies that the superconductivity gap in the copper oxide plane is isotropic.

Evidence for the existence of the superconductivity gap had already been seen in studies of the oxide superconductors with far-infrared absorption or tunneling techniques. The magnitude of the gap determined by the earliest experiments varied over a wide range—from 3 to 11 times k $T_c$. Robert Dynes of AT&T Bell Labs told us that by now about four different groups doing tunneling experiments on the Y-Ba-Cu-O material have reported consistent results. One continuing puzzle is the apparent presence of structure within the gap. Dynes said that the similarity of results despite different experimental preparations suggests that the effect being seen is an intrinsic property and not just a surface effect (the technique only probes within a coherence length of the surface).

Studies with infrared absorption are sensitive to behavior deeper within the superconductors. These studies are converging to about the same value of 8 k $T_c$ as determined by photoemission work. Joseph Orenstein and Gordon Thomas of AT&T Bell Labs, who have made some of the measurements, cautioned that the behavior of the low-temperature absorption spectrum does not exactly fit the BCS mold but shows some structure within the gap. IBM researchers Zack Schlesinger, Reuben Collins and Fred Holtzberg, with George Crabtree and Ulrich Welp of Argonne National Laboratory, announced at a January conference in Aspen on highly correlated electron systems that they found no evidence of the spurious states in the gap when they "untwinned" the crystal, that is, separated different orientations, and looked only at polarizations perpendicular to the chains of copper oxide. The gap appears isotropic within the copper oxide plane. Schlesinger, Collins and Holtzberg have consistently measured a gap of about 8 k $T_c$ since their 1987 experiment on a single twinned crystal.

## Theoretical interpretations

The photoemission data indicate some unusual behavior in both the superconducting and normal states. The gap is isotropic but somewhat larger than expected for a BCS-type material. Moreover, the intensity decrease in the gap is smaller than the intensity increase seen in the peak just below the gap as the material goes superconducting, whereas the Fermi liquid theory requires that these changes offset each other. The Fermi distribution in momentum is consistent with that of a traditional Fermi liquid in the normal state, but the energy distribution is not. In the words of Patrick Lee (MIT), "There is a large Fermi surface, and theorists must be prepared to deal with it, but as shown by other measurements of unusual behavior, such as resistivity and the Hall effect, it's not your garden-variety Fermi liquid."

Regarding the isotropic superconductivity gap, Paul Horn (IBM) told us that the simplest interpretation would be that of an s-wave BCS-type pairing. However, he cautioned that the experimental resolution cannot rule out states in the gap or other exotic effects.

Some are describing the oxide superconductors as "marginal" Fermi liquids, a phrase coined by five theorists. Before the results from the angle-resolved photoemission studies were known, these five—Chandra Varma, Peter Littlewood and Stefan Schmitt-Rink (AT&T Bell Labs) and Elihu Abrahams and Andrei Ruckenstein (Rutgers University)—had set out to explain[6] the collection of anomalies in the behavior of high-temperature superconductors that had been observed in other types of studies. They found one phenomenological hypothesis about the excitation spectrum that could account for the observed behaviors. Their hypothesis predicted that the width of the quasiparticle peak varies linearly with its energy separation from the Fermi surface, consistent with the new data from photoemission. Varma said that the phenomenological hypothesis points to an s-wave attractive interaction between electrons and leads to a calculated value for the full superconductivity gap of 7–8 k $T_c$ at zero temperature.

Philip Anderson (Princeton University), who has championed the resonating-valence-bond theory, differs even further with those who have interpreted the photoemission data as support for more traditional approaches. On the contrary, he feels, the photoemission data are the key that unlocks the whole subject. He told us that the experimenters have missed the most significant features of the data—the large, broad shoulder at higher binding energies and the sharpness of the rise that the experimenters interpret as a "peak." Although the researchers attribute the shoulder to background, Anderson interprets it as an intrinsic part of the data. In his view, the peak is markedly asymmetric and is more properly described as a "cusp." Anderson feels that the entire spectrum is consistent with what is expected in the RVB theory: The two particles must share the phase space between them, and thus two cusp-like singularities are expected. This picture, he feels, fits the details of the energy spectra both above and below the critical temperature better than the Fermi liquid interpretation.

Although coming from a different perspective than Anderson, George Sawatzky (University of Groningen, The Netherlands) agrees that the "background" is an intrinsic part of the spectrum. Sawatzky, however, feels that it could correspond to the incoherent part of the electron spectrum.[7] Even in a true Fermi liquid one expects to see a both peak and a higher energy structure. The relatively low-intensity peak then would correspond to quasiparticle states consisting of an electron surrounded by a halo of something like magnons, low energy scale excitons, phonons or something else with a low-energy-scale (on the order of 0.1 eV). Whether the observed behavior is consistent with a Fermi liquid, however, depends on other details of the spectrum.

—Barbara Goss Levi

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