

Schottky formula to be $S = 2qI_B$, where q is the charge of the carriers and I_B is the backscattered current. As the temperature is increased to exceed the applied voltage (that is, $kT > qV$), the form of the noise crosses over to the more complicated Johnson–Nyquist formula.

Results

Part a of the upper figure on page 18 shows the current noise versus backscattered current measured at a temperature of 25 mK by the French group. The noise, measured in a frequency range of 4 to 8 kHz over a time of 25 minutes, is well fit by Schottky noise with slope appropriate for particles of charge $e/3$. Analogous measurements for the $\nu = 4$ integer quantum Hall state yielded data closely fit by Schottky noise of whole electrons. Glatli suggested that the deviation at higher currents is due to the quasiparticles' statistics, which can be expected to be anyonic—intermediate between bosonic and fermionic.

Part b of the same figure shows data taken by the Israeli group at 57 mK, along with curves for Johnson–Nyquist noise due to particles of charge $e/3$ and e . (The French researchers also have data analogous to this, but with error bars and background levels comparable to their data in part a.) The noise was measured near 4 MHz and, because of the much lower levels of amplifier noise, integration times of about

5 seconds could be used.

A natural extension for both groups will be to study the noise at other filling factors. The Israeli group, for example, saw clear quantum Hall plateaus in its samples at $\nu = 2/5$, $3/5$ and $2/3$, but has not yet studied the noise of any of these. At $\nu = 2/5$, both the current and the quasiparticle charge ($e/5$) will be smaller, making the sensitivity of the measurements even more critical. In addition, contributions from $e/3$ quasiparticles at $\nu = 2/5$ may further complicate the analysis. (Goldman published measurements of $e/5$ charges at $\nu = 2/5$ using the quantum antidot system in 1996.⁷)

Physics in quantum Flatland

How “real” are the quasiparticles that these groups have detected? Theorist Steven Girvin of Indiana University points out that Laughlin’s theory doesn’t just explain the fractional quantum Hall effect, rather it demonstrates that the effect *requires* that such quasiparticles exist. He stresses that a quasiparticle can be pinned at a definite location, and because its state is then completely determined by the location (there is no degeneracy), the behavior is just as for an elementary particle.

Girvin offers the charming analogy of life near absolute zero in a quantum Hall Flatland: “Flatland particle theorists decide that the apparently fea-

tureless vacuum in which everyone lives each day is actually a roiling sea filled with strange but invisible objects that have precisely three times the charge of an ordinary quasiparticle. To study this possibility, a Flatland high-energy particle accelerator is constructed that can reach the unprecedented energy scale of 10 K. Upon smashing together three charged particles, it is found that they do indeed temporarily coalesce into an object with the bizarre property of having charge $3q$. It is decided to name this short-lived object the electron.”

“If the gap were 10 GeV instead of 10 K,” Girvin says, “we (living at room temperature) would have no trouble accepting the concept of fractional charge.”

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Tunneling Experiments in High- T_c Superconductors Resolve a Puzzle

A key question regarding high-temperature superconductors has been the nature of the pairing state of the electrons responsible for the supercurrent: Do the electrons couple in an s-wave state, as in conventional superconductors, or in a d-wave state, specifically $d_{x^2-y^2}$, whose wavefunction resembles a four-leaf clover. The argument was largely settled in favor of d-wave symmetry when several precise experiments were able to sense the phase of the electron-pair wavefunction and found that it changed signs, suggestive of the alternating positive and negative lobes of the d-wave clover leaf. But not all the evidence lined up: One study of the Josephson tunneling by Robert Dynes and his colleagues at the University of California, San Diego, simply wasn’t compatible with a d-wave interpretation.¹

By a clever twist on the original tunneling experiment, the situation now appears to be resolved in favor of a d-wave, with some admixture of s-

▶ Like the pea that disturbed the sleep of the fairy-tale princess, a Josephson tunneling experiment upset the consensus favoring a d-wave pairing of the electrons in high-temperature superconductors. Further studies of the tunneling behavior have now resolved the discrepancy.

wave.² To conduct this new measurement, Dynes and his San Diego group teamed with John Clarke and others at their sister institution in Berkeley. They performed separate but similar experiments using crystals grown both by Brian Maple and his group at San Diego and by Don Ginsberg and his team at the University of Illinois at Urbana–Champaign.

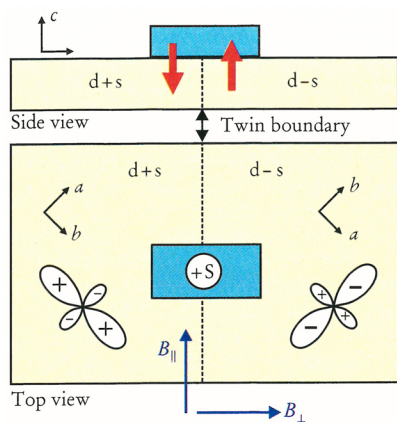
The view along the c axis

All of the early phase-sensitive studies of the electron-pairing state in the high- T_c copper oxide materials had probed these materials in the plane

containing the copper and oxygen atoms—that is, the ab plane. In their 1994 experiment, the San Diego group looked in a different direction: along the c axis, perpendicular to the ab planes.

Specifically, Dynes and his group measured the Josephson pair tunneling current along the c axis from conventional lead superconductors across thin insulating layers into crystals or thin films of yttrium barium copper oxide, commonly called YBCO. Lead is an s-wave superconductor, so the researchers expected to see a tunneling current only if the YBCO were also in an s-wave state; if the YBCO were in a d-wave state, tunneling from the positive lobe would cancel the tunneling from the negative lobe. The experiment came down on the side of s-wave symmetry.

The picture of the pairing state in YBCO is not quite so simple, however. In YBCO, the lattice is orthorhombic—that is, the lattice spacings are slightly



TO DETERMINE THE PAIRING STATE of electrons in YBCO, a high- T_c superconductor (yellow), researchers measured² the tunneling currents (red arrows) from YBCO into lead (blue) along the c axis, both for magnetic fields parallel to the twin boundary ($B_{\parallel}$) and for fields perpendicular to the boundary ($B_{\perp}$). The currents should be different for different field angles if the electron-pair wavefunction is $(d+s)$ -wave in one crystal domain and $(d-s)$ -wave in its twin. The a and b crystal axes are reversed in the twin domains.

different along the a and b axes. As a result the $d_{x^2-y^2}$ state is expected to be somewhat distorted: the positive lobes are not equal in size to the negative lobes.

YBCO also contains twin boundaries, at which the directions of the a and b axes reverse (see the figure above). If the pairing in YBCO is predominantly d -wave, the phase of the $d_{x^2-y^2}$ orbital should be maintained across the twin boundary: The positive lobe should lie along the same direction in both twins, but the relative sizes of the lobes will change, as illustrated in the figure. The resulting wavefunctions can be written as sums of a pure $d_{x^2-y^2}$ -state and an s -wave state, specifically as $d+s$ and $d-s$.

A new look

To take these complexities in YBCO into account, the Berkeley and San Diego groups studied tunneling from a selection of carefully grown YBCO crystals, each of which had twin domains separated by a single twin boundary. To construct a tunnel junction, the researchers deposited an insulating layer and a lead counterelectrode on top of the crystal, straddling the twin boundary, as shown in the figure. A magnetic field was applied parallel to the junction.

With this junction, the current into the lead was a sum of the tunnel currents from each of the twin domains. The presence of the twin boundary provided the researchers with an additional probe of the pairing symmetry. If the YBCO were predominantly s -

rotated the direction of the magnetic field. When the magnetic field was perpendicular to the twin boundary, the researchers expected a cancellation between the oppositely directed flows that would reduce the net current. (The cancellation was not perfect because the lead counterelectrode was not always exactly centered on the twin boundary.) They still expected the plot of the critical current to have the same Fraunhofer form as an ordinary junction, albeit with a lower peak current.

When the magnetic field was parallel to the twin boundary, however, the researchers expected the flux to

wave, the twin boundary would have no effect on the s -component and the Josephson critical current would have the same magnetic field dependence as a junction between ordinary superconductors; it would exhibit a Fraunhofer pattern, with a maximum current at zero magnetic field, independent of the direction of the applied field.

If, on the other hand, YBCO were predominantly d -wave, then the s -component would change sign across the twin boundary and cause a significant effect; the Josephson current along the c -axis would flow in opposite directions on each side of the twin boundary. To test for the presence of such oppositely directed currents, the researchers

cancel the phase difference between the two domains and cause the currents to flow in the same direction. The maximum current therefore should occur not at $B=0$ but at a field value corresponding to a half-integer flux quantum. For these parallel fields, the Berkeley and San Diego teams anticipated that the field dependence of the critical current would have a dip rather than a peak at $B=0$. That is exactly the signature they saw.

The Berkeley-San Diego-Illinois experiment established that the electron-pair wavefunction in YBCO has an s -wave component to it, and that the s -wave component changes sign across a twin boundary. The results are fully compatible with a $d_{x^2-y^2}$ -wave symmetry with an admixture of s -wave as a result of the distortion by the underlying orthorhombic symmetry. Recent experiments using angle-resolved photoemission in a bismuth-based cuprate³ and Josephson interference in a thallium-based copper oxide⁴ indicate that these other high- T_c compounds, which do not have the orthorhombic distortions of the YBCO, are nearly pure d -wave.

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A Hint of T Violation in a High- T_c Superconductor

Unexpected behavior in a tunneling experiment on one of the high-temperature superconductors has led the experimenters to conclude that they are seeing broken time-reversal symmetry.¹ The evidence, if confirmed, would indicate a violation of time reversal only at the surface, but it nevertheless has created a lot of interest, especially among theorists who predicted some type of symmetry breaking in unconventional superconductors even in the bulk.

The specific evidence comes from a collaboration between Laura Greene and her group at the University of Illinois at Urbana-Champaign and Chad Mirkin and his coworkers at

Northwestern University. This team measured the tunneling current from copper, a normal metal, through an insulator into yttrium barium copper oxide (YBCO), a high- T_c cuprate. The current was directed into the plane that contains the copper and oxygen atoms.

The behavior that caught the experimenters' attention concerned the previously observed² zero-bias conductance peak—that is, an excess current that flows even when no voltage is applied. This peak in the plot of conductance as a function of bias voltage has been known to split when a magnetic field is applied, but the big surprise was to see it split even when no magnetic field was applied, once the