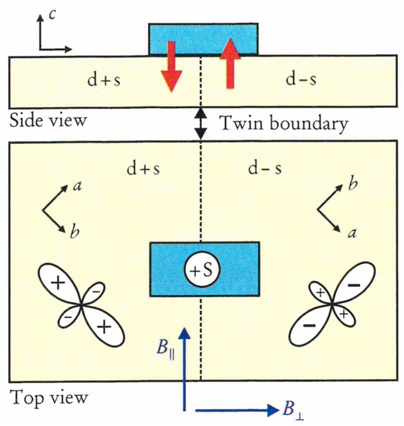

TO DETERMINE THE PAIRING STATE of electrons in YBCO, a high-T_c superconductor (yellow), researchers measured[2] the tunneling currents (red arrows) from YBCO into lead (blue) along the *c* axis, both for magnetic fields parallel to the twin boundary ($B_\parallel$) and for fields perpendicular to the 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-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 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 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 cuprate[3] and Josephson interference in a thallium-based copper oxide[4] 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 observed[2] 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 temperature was lowered below about 7 K. (An earlier experiment had hinted at the zero-field splitting.[3])

The splitting of the conductance peak indicates time-reversal symmetry breaking: It reveals an energy splitting between states that are time-reversed pairs of one another. A magnetic field, which breaks time-reversal symmetry, can cause such a splitting, so whatever is causing the splitting at $B = 0$ may itself be violating time-reversal symmetry. One such mechanism, suggested by Mikael Fogelström, Dierk Rainer and Jim Sauls of Northwestern,[4] is the appearance near the surface of what they call a subdominant pairing interaction—that is, one that normally cannot compete with the d-wave pairing (corresponding to an electron-pair wavefunction resembling a four-leaf clover) that prevails in the bulk. To explain the zero-bias splitting, the component of the electron wavefunction associated with the subdominant interaction must have a different symmetry from the d-wave—most likely s wave. In the Northwestern theory, the relative phase between the s wave and d wave leads to an energy splitting between the time-reversed surface states, which is seen directly as a splitting of the zero bias conductance peak. The data produced by the Illinois–Northwestern group are in reasonable agreement with the calculations of Sauls and his colleagues.

Zero-bias conductance peaks can also be caused by magnetic impurities in the tunnel junction. However, Greene argues that such an explanation is inconsistent with the data. Instead, she and her colleagues assert that the zero-bias peak stems from Andreev scattering—that is, the interaction of an electron-like quasiparticle with a superconducting pair, which breaks the pair and causes the quasiparticle to be reflected as a hole.

Greene is eager for other experiments to confirm her group's results. And she's watching to see whether their results are related to those of several other experiments, which also indicate the possible appearance of a second order parameter.

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Stanford Wants to Build a TeV Linear Collider with Japan

As the small test accelerator for the proposed 20-km electron–positron collider nears completion, SLAC and KEK have drafted a memorandum of understanding.

Four years ago, accelerator physicists at the Stanford Linear Accelerator Center (SLAC) began construction of the Next Linear Collider Test Accelerator (NLCTA), a 42-meter-long experimental prototype segment of what they call the "Next Linear Collider." The NLC they hope to build early in the next century would be a face-to-face pair of 10-km linacs firing electrons and positrons at each other with collision energies up to a TeV (10^{12} electron volts).

The highest e^+e^- collision energy now available to experimenters is the 200 GeV provided by LEP, the 27-km-circumference storage-ring collider at CERN. But the theorists tell us that crucial new physics is bound to manifest itself when point-particle (electron, positron, muon, quark or gluon) collision energies approach a TeV. Because protons, by contrast, are composite particles, a proton collider will have to get up to significantly higher energies to explore this promised land. For particles as light as the electron, a TeV e^+e^- storage ring is excluded by synchroton radiation loss, which increases as the inverse fourth power of the mass.

Now the NLCTA is nearing completion. (See the photo on page 22.) But even in its various incomplete stages, the test accelerator has already provided significant results[1] with regard to the accelerator technologies the NLC designers hope to exploit: non-superconducting, klystron-powered, multibunch radio-frequency acceleration at an "X band" frequency of 11.4 GHz.

This is, of course, not the only interesting option for a TeV lepton collider in the next decade: The DESY laboratory in Hamburg, for example, has opted for a superconducting RF linac operating at 1.3 GHz. CERN, for a time, actively pursued the notion of a "two-beam" linac, with a low-energy, high-current auxiliary electron beam replacing the klystrons as the source of microwave power. Even more exotic is the idea, put foward by Robert Palmer (Brookhaven) and collaborators, that one could build a circular 4-TeV $\mu^+\mu^-$ collider only a few km in diameter. Each of these choices has its own particular strengths and difficulties. But one can argue that the NLC option, or a similar design under study in Japan, involves the smallest extrapolation from accelerator technology already in the field.

Memorandum of understanding

Four months ago, SLAC director Burton Richter and Hirotaka Sugawara, director of KEK, the Japanese high-energy laboratory near Tokyo, drafted a memorandum of understanding stating that the two labs want to work together toward the design of a TeV linear collider, for which a site would eventually be chosen by the participating governments, somewhere in the US, Japan or some other country in the Pacific region. "Originally," Richter told us, "Sugawara, [DESY director] Bjorn Wiik and I had intended to study various technical options and then proceed to a truly worldwide collaboration. But now Wiik intends to complete a superconducting RF linac design for a site adjoining DESY, and submit it to the German government for funding. Sugawara and I think the room-temperature X-band option is at least as good, and certainly more ready. So now we have to proceed without DESY."

Because Sugawara, unlike Richter, is a government official, formal signing of the memoradum of understanding must await the approval of the Japanese science ministry, sometime in the next month or so. The non-governmental Japanese High Energy Physics Committee has already given the proposed joint R&D program its blessing. SLAC can continue its own R&D effort toward the collider without special new DOE approval at this juncture. Nor would the signed memorandum commit either government to the NLC.

DOE approval would, however, be required for the Conceptual Design Report (CDR) phase, which Richter hopes would begin early in 1999. In the meantime, the pace of the SLAC effort will depend somewhat on the priority assigned to a TeV e^+e^- collider by the DOE High Energy Physics Advisory Panel's subpanel on planning for the future of US high-energy physics. The subpanel, chaired by Fred Gilman (Carnegie–Mellon University), will report its recommendations to HEPAP early next year.

In the CDR phase, the collaboration, having arrived at something like an optimal parameter set, would produce a detailed engineering design. The site