

light has traversed 8, 12, 16, and 20 angled interfaces, respectively.

Ghosh and Fischer used the multiple cuvettes shown in the figure to increase the spread of the refracted rays enough for the separate beams to be seen with a CCD camera. But the experimenters were also able to measure splitting that occurs at a single interface using a position-sensitive detector, which recorded the tiny movement of a laser beam after it had traversed the interface. Simultaneous modulation of the laser beam's polarization between right- and left-handed circular light permitted the detection of beam movements as small as 10 nanoradians.

With such a detector, the experimenters determined the angle of reflection of light that bounced off a single interface from within a chiral liquid. Contrary to the lesson taught in school, the angle of incidence in this case is not equal to the angle of reflection. No great principle is being violated. The experimenters explain that the handedness of the circularly polarized light changes upon reflection, so that the reflected light sees a different refractive index n than the incident light. From the boundary conditions on the electromagnetic waves at the inter-

face, one arrives at a requirement equating the tangential components of the incident and reflected wavevectors, k_i and k_r . Thus, the condition $k_i \sin \theta_i = k_r \sin \theta_r$ governs the reflection.

The splitting at a single surface is a measure of the sample's circular birefringence—that is, the difference in refractive index seen by the two circularly polarized beams. Ghosh and Fischer found that the circular birefringence measured by the angular splitting is consistent with that determined by conventional optical-rotation measurements. Thus, they note, the two techniques yield equivalent information. In optical rotation, however, the magnitude of the rotation of the polarization vector is proportional to the distance traveled through the sample. By contrast, angular splitting is determined at the surface and is independent of the sample thickness. The angular splitting technique thus might hold promise for use with very small samples, such as are required in microfluidics or thin films.

Barbara Goss Levi

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Superconductor forms domains that break time-reversal symmetry

Two interference experiments—one using the Kerr effect, the other using the Josephson effect—confirm strontium ruthenate's exotic pairing.

When a superconductor's temperature drops below its critical value, some of the most loosely bound electrons assemble into a single, Bose-Einstein ground state. Locked together, the electrons flow through the lattice with unimpeded ease.

To reach that remarkable state, electrons, being fermions, must pair up to form bosons whose total spin S is an integer. Pairs of spin- $1/2$ electrons have two choices of S : 0 or 1, antiparallel or parallel. Because a pair of identical fermions must have an antisymmetric wavefunction, fixing S also constrains the pair's total orbital angular momentum L : If $S = 0$, L must be an even integer; if $S = 1$, L must be an odd integer.

How electrons follow those rules and actually pair up depends on the symmetry of the lattice and on what fluctuations polarize and nudge the electrons together. In ordinary, Bardeen-Cooper-Schrieffer superconductors, lattice vibrations mediate the pairing and S and L are

both zero. By analogy with atomic orbitals, the pairing is known as s -wave.

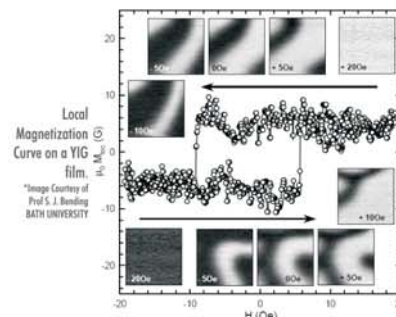
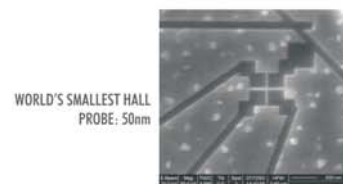
When L is nonzero, the paired electrons, like electrons in single atoms, can orbit each other in more than one configuration. No one has yet identified the mediating fluctuations in high- T_c cuprates, but experiments have established that the pairing is a cloverleaf-shaped variety of d -wave ($S = 0$; $L = 2$).

Yoshiteru Maeno of Kyoto University discovered strontium ruthenate's superconducting state in 1994. Strontium ruthenate (Sr_2RuO_4) has the same lattice structure as lanthanum cuprate (La_2CuO_4), the parent compound of the first family of high- T_c superconductors. Based on the resemblance, one might expect the ruthenate's superconductivity to occur in the RuO_4 planes and its pairing to be d -wave.

The superconductivity turned out to be two-dimensional, but the preponderance of evidence soon favored p -wave pairing ($S = 1$; $L = 1$). Indeed,

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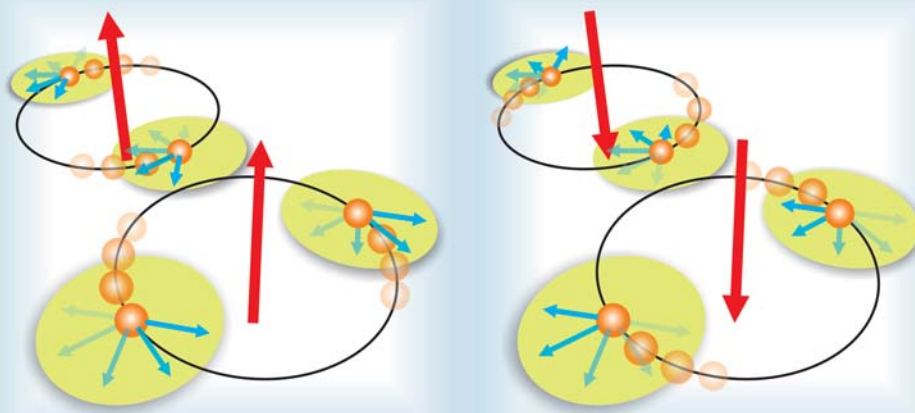


Figure 1. Strontium ruthenate's superconductivity takes place in the parallel planes formed by its ruthenium and oxygen atoms. When the electrons pair up below the critical temperature, their spin angular momenta (blue arrows) rotate in the plane and their orbital angular momenta (red arrows) point out of the plane. If one could reverse the pairs' spin and motion, their total orbital angular momentum would flip, breaking time-reversal symmetry. (Adapted from A. P. Mackenzie, Y. Maeno, *Rev. Mod. Phys.* **75**, 657, 2003.)

strontium ruthenate has become the archetypal *p*-wave superconductor (see the article by Maeno, Maurice Rice, and Manfred Sigrist, *PHYSICS TODAY*, January 2001, page 42). Direct, compelling proof came two years ago. Ying Liu of the Pennsylvania State University and his collaborators sandwiched a strontium ruthenate crystal between two Josephson junctions and found a telltale phase shift.¹

But in a 2D superconductor whose lattice, like strontium ruthenate's, has tetragonal symmetry, no fewer than 13 different varieties of *p*-wave pairing are possible. Now, teams led by Aharon Kapitulnik of Stanford University and Dale Van Harlingen of the University of Illinois at Urbana-Champaign, have determined which one prevails in strontium ruthenate.^{2,3}

The pairing, denoted by its relative linear momentum as $p_x \pm ip_y$, is not only the most theoretically plausible, it's also among the most interesting. It breaks time-reversal symmetry and forms ferromagnet-like domains. And it might even sustain half vortices that could carry out fault-tolerant quantum computation.

Reversing time

As figure 1 shows, electrons with $p_x \pm ip_y$ pairing orbit each other in a definite sense (embodied mathematically as $+ip_y$ or $-ip_y$). Reversing their motions therefore flips their orbital angular momentum vector and constitutes broken time-reversal symmetry (TRS).

TRS breaking is not what led Maurice Rice and Manfred Sigrist—and, independently, Ganapathy Baskaran—to propose $p_x \pm ip_y$ pairing for strontium ruthenate back in 1995.⁴ Rather, they based their case on strontium ruthenate's resemblance to two other materials: SrRuO₃ and superfluid helium-3.

Strontium ruthenate's chemical rela-

tive SrRuO₃ is a ferromagnet. As such, it favors parallel, not antiparallel, spins and, consequently, *p*-wave, not *s*-wave, pairing.

Helium-3 atoms are fermions and must pair up to form a superfluid. Helium-3 has two principal superfluid phases, A and B, which have different pairing and form at different temperatures and pressures. In their respective normal states, strontium ruthenate and helium-3 both behave like Landau-Fermi liquids. If, the three theorists argued, the resemblance is preserved below T_c , strontium ruthenate would pair up like the A or B phase of helium-3.

In 3D superfluid helium-3, the B phase is energetically more favorable than the A phase, which has the TRS-breaking form $p_x \pm ip_y$. But in strontium ruthenate, whose superconductivity is 2D, the preference is reversed and the analog of the A phase wins—at least on paper.

Three years after Rice, Sigrist, and Baskaran proposed the $p_x \pm ip_y$ pairing, Graeme Luke and his collaborators bombarded a superconducting strontium ruthenate crystal with positively charged muons.⁵ During their brief spell in the lattice, the muons precess in the local magnetic field and then decay into positrons and neutrinos. Each positron flies off in the same direction as the spin of its muon parent. By mapping the positron distribution, Luke inferred a distribution of moments consistent with $p_x \pm ip_y$ pairing.

Kapitulnik set out to measure the TRS breaking directly. To do so, he refined a technique he developed 15 years ago to refute a so-called anyon theory of superconductivity (see *PHYSICS TODAY*, February 1991, page 17).

His technique relies on the polar Kerr effect. When circularly polarized light reflects off a TRS-breaking surface,

it picks up a rotational phase shift. But screw dislocations and other non-TRS-breaking features can hide or mimic the sought-for signal.

Kapitulnik realized that two beams of opposite circular polarization would acquire, on reflection, a set of rotations of equal magnitude, but not necessarily of equal sense. Although the rotation due to TRS breaking would be in the same sense for the two beams, all other potential rotations would oppose each other. Combining two reflected beams in an interferometer would therefore double the TRS-breaking rotation while canceling the rest.

The expected rotation in strontium ruthenate is tiny. Compounding the experimental challenge is strontium ruthenate's low T_c of just 1.4 K. To avoid heating the sample and destroying the superconductivity, the beams must be feeble. The Stanford light source, a superluminescent light-emitting diode (SLED), runs at 1–2 microwatts.

To meet those challenges, Kapitulnik, his graduate student Jing Xia, and their collaborators adapted the earlier anyon setup. In outline, the experiment works as follows. Continuous light from a broadband SLED centered at a wavelength of 1550 nm is split into two beams of orthogonal linear polarization, X and Y. The beams travel along two paths, A and B, toward the helium-cooled chamber that houses the sample. Polarization-maintaining optical fibers constitute most of each path. A is 8 mm longer than B.

Just before the beams reach the sample, they pass through a focusing lens and $1/4$ -wave plate that turns the X beam into right-circularly polarized light and the Y beam into left-circularly polarized light.

After reflecting off the sample, the beams pass back through the $1/4$ -wave

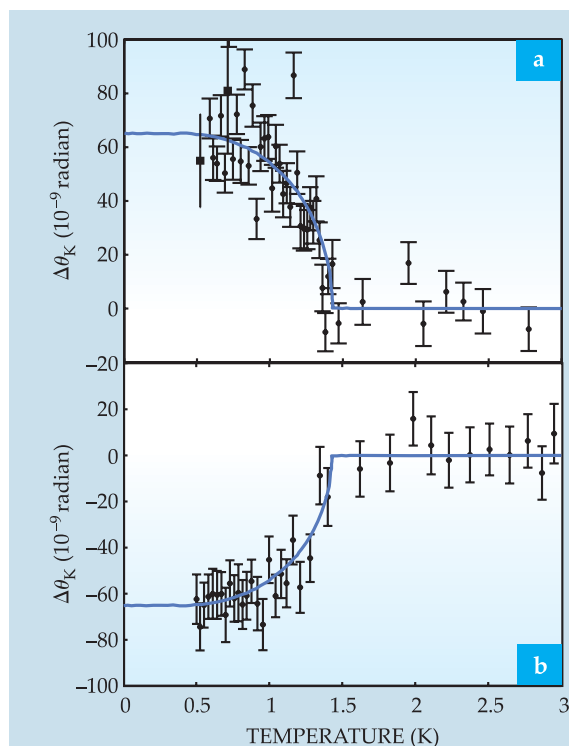


Figure 2. Electron pairs that break time-reversal symmetry in superconducting strontium ruthenate shift the phase of circularly polarized light by the Kerr angle $\Delta\theta_K$. They also form domains that can be oriented by an applied magnetic field. Here, the measured rotation is plotted against temperature above and below T_c . In (a), the applied field was +93 oersteds; in (b), -47 Oe. The curves represent a simple model. (Adapted from ref. 2.)

plate, which restores their linear polarization, and back through the focusing lens, which switches their positions for the return trip: The X beam now follows the B path and the Y beam follows the A path. The trip ends at the interferometer, which recombines the beams. If the sample breaks TRS, the fringes shift.

To measure the shift, two additional tricks are needed. First, the SLED has a deliberately short coherence length. Wavefronts in the two beams therefore lose their mutual coherence unless they travel the same distance. When the interferometer recombines the beams, only the wavefronts that have made the complete trip to the sample and back (A + B or B + A) can produce fringes. All other backward-traveling light, from reflections off the various optical components, contributes a flat, incoherent background.

The second trick is a standard one in interferometry. In principle, one could determine the rotation directly by measuring how far the fringes shift, but a more accurate method is to impose a periodic phase modulation on the beams and look for displacements in the harmonic signal.

In the Stanford setup, the X beam is modulated on its way to the sample, whereas the Y beam is modulated on its way back. When the two beams reach the interferometer, they interfere and produce a time-varying intensity that has various harmonic components. The TRS-breaking signal shows up at the

modulator's 5-MHz frequency; the component at twice the modulation frequency is proportional to reflected coherent intensity. Locking onto both frequencies yields a precision of 10 nanoradians.

Figure 2 shows the result of two runs, both of which began with the sample temperature at 0.5 K. Deep in the superconducting state, TRS breaking appears as a rotation of about 65 nanoradians. When the sample was allowed to warm up, the rotation narrowed then vanished at T_c . Recently, Victor Yakovenko of the University of Maryland calculated the rotation and came up with a similar value.⁶

In orbiting each other, the paired electrons behave like tiny magnets. Figure 2 also shows the result of applying an external magnetic field to train the pairs to adopt either $p_x + ip_y$ or $p_x - ip_y$ pairing. In both runs, the field was applied while the sample was at its lowest temperature and then turned off before the sample warmed up. Evidently, electron pairs in strontium ruthenate respond to a magnetic field like the electron spins in a ferromagnet.

The Stanford researchers could also infer the length scale over which the pairs line up—that is, the size of $p_x + ip_y$ or $p_x - ip_y$ domains. They pointed their beam at different parts of the same sample at zero magnetic field. Based on the size of their beam, they estimate the domains to be about 50 μm across.

Even before strontium ruthenate's

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NIST Sample



Si (111) (7x7)
Image courtesy of Dr H. O. Ozor
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Gold on mica



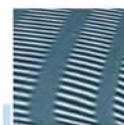
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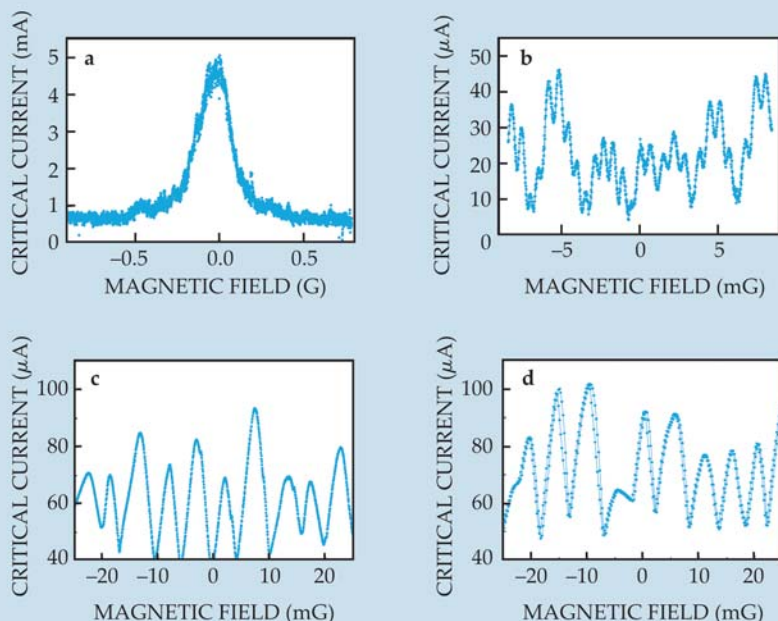


Figure 3. The current through a Josephson junction is ordinarily strongest at zero magnetic field. That's the case in (a), where either one domain or several domains of the same phase crossed the junction. But in (b), (c), and (d), multiple domains of different phase crossed the junction, each making an out-of-phase contribution to the signal. (Adapted from ref. 3.)

superconductivity was discovered, Grigori Volovik and Lev Gorkov predicted that p -wave superconductors could form domains.⁶ Like ferromagnetic domains, p -wave domains would show up on the surface of a material as alternating patches of magnetism.

Unfortunately for experimenters, the domains' magnetization is likely to be intrinsically weak. Worse, magnetic fields in superconductors induce surface currents that screen the field. Last year, Stanford's Kathryn Moler and her collaborators swept a SQUID magnetometer across a sample of strontium ruthenate but didn't detect domains.⁸

When Van Harlingen began working on strontium ruthenate eight years ago, his aim was to use Josephson junctions to verify the superconductor's p -wave pairing. In a Josephson junction, electron pairs tunnel across a narrow insulating gap between two superconductors. Applying a variable magnetic field sets up a phase gradient along the junction and causes the critical tunneling current I_c to oscillate in a diffraction-like pattern:

$$I_c(\Phi) \propto \sin(\pi\Phi/\Phi_0)/(\pi\Phi/\Phi_0).$$

Here, Φ is the magnetic flux that threads the junction and Φ_0 is the magnetic flux quantum $h/2e$.

If the pairing itself has a phase dependence, departures from the sinc pat-

tern can occur. To see them, the phase dependence has to manifest itself along the length of the junction through which $I_c(\Phi)$ is measured. One way to provide that opportunity is to make a junction that extends along one crystal face around a corner to the next. Then, phase differences in the current through the two faces may show up in the combined signal $I_c(\Phi)$.

In 1995 Van Harlingen and his collaborators used a corner junction to confirm that the high- T_c cuprates have $d_{x^2-y^2}$ pairing.⁹ Because the pairing's phase swaps sign with each 90° turn, the current on either side of a 90° corner exactly cancels. Instead of a single peak at zero magnetic field, Van Harlingen saw two symmetric peaks on either side of a minimum.

Because $p_x \pm ip_y$ pairing supports domains, its phase dependence can show up in $I_c(\Phi)$ even without an angled junction. For their experiments with strontium ruthenate, Van Harlingen, his graduate student Françoise Kidwingira, and their collaborators used straight junctions. Occasionally, they saw a sinc pattern, as exemplified by panel a of figure 3. But most of the time, $I_c(\Phi)$ revealed an oscillatory pattern from two or more domains, as the other three panels show.

In some runs, they observed a sinc pattern from one face, but when they

looked at the current through an orthogonal face, they observed an oscillatory pattern—as if the domains were aligned in one direction, but out of phase in the other.

The domains aren't static. $I_c(\Phi)$ varied from run to run in the same sample, exhibiting telegraph noise and hysteresis. By comparing their data with a simple model, the UIUC team inferred a domain size of about 1 μm. The UIUC estimate differs in order of magnitude from the Stanford estimate. It's not clear why.

Half vortices

In addition to domains, $p_x \pm ip_y$ pairing supports another intriguing phenomenon: half vortices. The pairs' full order parameter is the product of the pairing potential Δ and the total spin vector $\mathbf{d}$. Under certain circumstances, Δ and $\mathbf{d}$ can both change sign after only one half rotation in real space, whereupon the order parameter regains its starting value. The result, as was first appreciated for the A phase of helium-3, is a half vortex of flux $h/4e$.

Paradoxically, oppositely rotating half vortices have higher binding energy and are harder to separate than integer vortices. The problem is spin-orbit coupling. If the angular momentum and spin vectors are aligned, their dot product contributes an additional, energy-boosting term. In 1985 Volovik and the late Martti Salomaa proposed that confining helium-3 in a thin film would reorient the atoms, minimize the coupling, and, they hoped, make the half vortices in helium-3 observable.¹⁰

In strontium ruthenate, spin-orbit coupling arises from the electrostatic tug of the positively charged ruthenium and oxygen ions on the electron pairs. Although experiments indicate the coupling is weak, it's still strong enough to prevent half vortices from forming.

Half vortices are interesting phenomena in their own right. And Moler, for one, is looking for them. But last year Sankar Das Sarma and Sumanta Tewari of the University of Maryland and Chetan Nayak of UCLA and Microsoft's Station Q proposed an application: fault-tolerant quantum computation.¹¹

The theorists' inspiration came from the half vortices' mathematical resemblance to quasiparticles that form in the $5/2$ fractional quantum Hall state. Last year Das Sarma, Nayak, and Microsoft's Michael Freedman, proposed using the quasiparticles for quantum computation (see PHYSICS TODAY, October 2005, page 21). Like the quasiparticles, the

half vortices have intrinsic degeneracies that can be tapped for quantum computation by moving the half vortices around each other. And because the degeneracy resides in a collective state, coherence is more robust.

For the scheme to work, the energy required to pull apart a half vortex pair must be small. To overcome the troublesome spin-orbit coupling, Das Sarma, Nayak, and Tewari propose an electromagnetic analog of Salomaa and Volovik's thin film idea: Apply a magnetic field to reorient the spins and suppress the coupling.

Five years ago Maeno, Rice, and Sigrist reviewed research on strontium ruthenate for PHYSICS TODAY. The title they picked, "The Intriguing Superconductivity of Strontium Ruthenate," now seems even more apt.

Charles Day

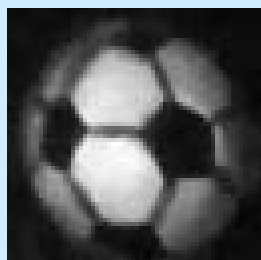
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physics update

Supplementary material related to these items can be found at www.physicstoday.org.

A single-pixel camera has been developed by researchers at Rice University. The device is part of an emerging shift from digital signal processing, in which analog signals are converted into their digital counterparts for processing, to computational signal processing, in which analog signals are fed in some suitable form directly into nonlinear processing algorithms. Instead of data-gathering pixels, the Rice camera uses a digital micromirror device—an array of micromirrors that can each adopt one of two orientations. A lens focuses an image onto the DMD; then the image is



reflected by a randomly chosen subset of the mirrors through another lens and focused onto a single photodiode. The photodiode

generates a voltage that serves as a coefficient for the particular DMD configuration. The image is sampled repeatedly with different DMD configurations, and the collection of measured voltages is processed to reconstruct the image. Typically, many fewer measurements are needed than the number of mirrors in the array, which leads to savings in data storage and processing. For example,

the image of a soccer ball shown here was taken with a 4096-mirror (64×64) camera and 1600 measurements. The tradeoff in the new scheme is between data compression and acquisition time rather than between resolution and number of sensors. Because the camera uses only one sensor (a photodiode in the prototype), the researchers say that "compressive sensing" can be adapted for imaging at wavelengths inaccessible to digital photography. The Rice results were reported at the Frontiers in Optics 2006 meeting of the Optical Society of America held in October in Rochester, New York. (See paper FWN3 among the Wednesday abstracts at <http://www.osa.org/meetings/annual/program/default.aspx>.) —PFS

Element 118 is discovered. At the Joint Institute for Nuclear Research in Dubna, Russia, 20 physicists from JINR and 10 from Lawrence Livermore National Laboratory in the US sent a beam of calcium-48 ions into a target of californium-249 atoms to briefly create three representatives of element 118, which lies just beneath radon in the periodic table and is therefore a kind of noble gas. In separate runs with about 2×10^{19} calcium projectiles each, one atom of element 118 appeared in the year 2002 and two more in 2005; the exhaustive analysis took until now to

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