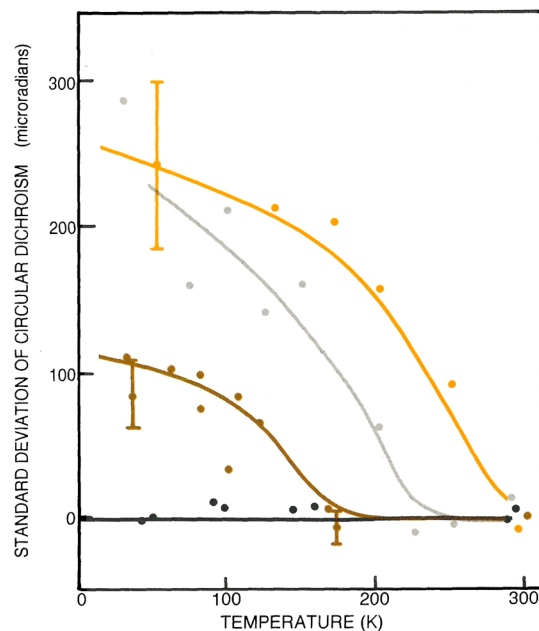


## THE HUNT FOR ANYONS IN OXIDE SUPERCONDUCTORS IS INCONCLUSIVE

As the date of the APS March meeting draws near, the conflicting results of two key experiments first aired by condensed matter physicists at last year's gathering are no closer to being resolved. Indeed a third experiment, reported this fall, has further clouded the picture. The conflicting evidence concerns whether or not high-temperature superconductors alter either the direction or ellipticity of polarized light passing through them. Such behavior might signal the breaking of time-reversal invariance in these new oxide materials—precisely the effect predicted by proponents of theories that invoke anyons, or exotic objects obeying fractional statistics, to explain the superconductivity.

Anyons are excitations that are neither bosons nor fermions. For bosons or fermions, an exchange of identical particles causes the wavefunction to be multiplied by a factor of 1 or  $-1$ , respectively, that is, the exchange produces a phase change of 0 or  $\pi$ . (See *PHYSICS TODAY*, November 1989, page 17.) For anyons, however, the phase change under the same operation may have *any* value. Anyons have been known to field theorists for some time,<sup>1</sup> but they were only recently identified as possible players in realizable situations.

Fractional phase changes stem from topological constraints and can occur only in two dimensions, so anyons are not expected in higher dimensions. However, they might appear in real physical systems that effectively confine electrons to two dimensions, such as the two-dimensional electron gas in which the fractional quantum Hall effect occurs or the copper oxide planes in oxide superconductors. Indeed, anyons have already been identified in the fractional quantum Hall effect: Several years ago theorists were uncertain whether to describe the collective excitations known as quasielectrons and quasiholes as fermions or bosons, but then Bertrand Halperin (Harvard) found that one could explain



**Standard deviation** of circular dichroism as measured at Bell Labs on thin films (brown), and on crystals of YBCO (gray) and bismuth oxide (orange) superconductors. The experimenters feel the data show an unexpected symmetry-breaking effect in the materials. Insulating films (black) show no signs of optical effects. (Adapted from ref. 6.)

their behavior most succinctly if one assumed they were anyons.<sup>2</sup> In the picture that has emerged, the quasiparticles are composite particles of magnetic flux tubes and charges. Many physicists like to imagine anyons in exactly this way, as charged particles associated with magnetic fluxes. Because of the Aharonov-Bohm effect, such quasiparticles would undergo a nonzero phase shift as they encircled each other, an operation akin to the exchange of identical particles.

Theories of anyon superconductivity grew out of the resonating-valence-bond theory proposed by Philip Anderson (Princeton) to explain high-temperature superconductivity although Anderson himself does not espouse anyons. (In fact, Anderson believes that other experimental data on high-temperature superconductors exclude the theories based on anyons.)

In his theory, the excitations are neutral, spin- $1/2$  particles called "spinons" and charged, spinless particles called "holons." In 1987 Robert Laughlin (Stanford) and Vadim Kal-meyer (now at the University of Illinois) associated these spinons and holons with the anyons that had just been used to explain the fractional quantum Hall effect.<sup>3</sup> As Laughlin explained to us, their key idea was that the spin-charge separation conceived by Anderson implies that there is a gauge force between the particles, as in the two-dimensional quantum Hall effect. Laughlin then found that this force was just the thing to cause superconductivity. Several variants of anyon superconductivity have since emerged, although all, Laughlin admits, are still at a primitive stage. These models assign a statistical phase of  $\pi/2$  to the anyons, which are then called semions.

## The clues

Anyons inherently violate both time-reversal invariance and parity because the phase change when one particle encircles another depends on the direction of the loop taken. The product of  $T$  and  $P$  may, however, remain invariant. In 1988 John March-Russell (Princeton) and Frank Wilczek (Institute for Advanced Study) suggested that these  $T$  and  $P$  symmetry violations might provide a signal for detection of anyons.<sup>4</sup> Even some theories of superconductivity that do not invoke anyons predict a violation of  $T$  and  $P$  invariance.

It is well known that materials that violate either time or parity invariance cause optical effects. One example of such effects, caused by parity violation alone, is the rotation of linearly polarized light as it passes through solutions of molecules with a definite handedness, such as sugar water. In this case, though, the rotation "unwinds," returning to its original polarization, if the light reflects back on itself. Another example, which breaks both  $T$  and  $P$  invariance, is the Faraday effect, in which linearly polarized light is rotated when it goes through matter in the direction of an applied magnetic field: The field destroys time-reversal invariance by establishing a definite direction within a sample. In this case reflection of the light on itself does not cause unwinding. In 1989 Xiao-Gang Wen (Institute for Advanced Study) and Anthony Zee (Institute for Theoretical Physics, Santa Barbara) noted that the presence of anyons in oxide materials might cause behavior analogous to the Faraday effect that would reorient the direction of linearly polarized light after it is reflected at right angles from the copper oxide planes.<sup>5</sup>

Unfortunately the anyon theory is not sufficiently developed for theorists to predict whether the sign of symmetry breaking is the same in successive layers, in a kind of ferromagnetic ordering, or whether it is opposite, as in antiferromagnetic ordering. The detected signal would of course be much greater in the former case and might be null in the latter case. Wen and Zee have recently made some semiquantitative predictions for the case of ferromagnetic ordering, valid at low frequencies only, but their results depend on such unknown parameters as the anyon mass and thus may be off by an order of magnitude.

## The hunt

Nevertheless the experimentalists have ventured out to see whether

there is a detectable signal of any kind. Great sensitivity and sophistication are required in measuring these optical effects to assure that all extraneous factors that might rotate the polarization are eliminated. One worry is a possible chirality in the inherent structure of the materials. For example, if the orientation of the copper oxide planes shifted slightly in each successive plane through the sample, that shift alone—even in the absence of anyons—could affect the polarization of light passing through the sample.

Kenneth Lyons and his colleagues at AT&T Bell Labs reported in an unannounced informal talk at the March APS meeting that they had positive evidence for optical effects in oxide materials.<sup>6</sup> At the same session Aharon Kapitulnik and his collaborators at Stanford countered with their finding of no signal whatsoever.<sup>7</sup> Last fall a group at the University of Dortmund, Germany, led by Hans Weber, also reported a positive result<sup>8</sup> but one that was at least ten times larger than that seen by the Bell Labs group. The Dortmund group measured rotations as large as those caused by the best magneto-optic materials.

The optical experiments might measure either dichroism or birefringence. Circular dichroism results when the material absorbs right-hand circularly polarized light more or less strongly than it does left-hand circularly polarized light: Circular dichroism changes the ellipticity of light. By contrast, circular birefringence occurs when light polarized in opposite senses travels at different speeds through the material: This effect rotates the axis of polarization. The apparatus used by the Bell Labs team measures circular dichroism of reflected light with a sensitivity of 25 microradians. Working with a laser wavelength of  $0.514\ \mu\text{m}$  and spot size of  $20\ \mu\text{m}$ , they initially measured the circular dichroism at 10 to 25 locations on the surface of thin films of  $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ . At each location the angle  $\phi$  specifying the circular dichroism was different, presumably because of the different orientations of domains within their sample. Thus Lyons and his colleagues computed the average value of  $\phi$ , which was consistent with zero, and took the standard deviation from this average as their measure of the circular dichroism within an individual domain. The standard deviation, plotted in the figure on page 17, is near zero down to a temperature just below 200 K and rises to a value of over  $100\ \mu\text{rad}$  as the temperature drops further. Subse-

quent measurements on crystal samples of both YBCO and  $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_8$  showed similar behavior but with a higher-temperature onset and values of  $\sigma_\phi$  that were two to three times larger. To check against possible extraneous effects unrelated to the superconducting properties, the Bell Labs group annealed the YBCO sample to convert it to an insulator. The circular dichroism then disappeared.

Lyons very carefully phrased his summary of the group's work for us: "There is clearly a breaking of the symmetry of the materials in some unexpected way well above the critical temperature that is correlated with the presence of superconductivity. We are not sure what is the nature of the broken symmetry, but it indicates a phase transition of some kind."

How certain can the Bell experimenters be that the effect they measured had no other origin? To cancel any sources of linear birefringence along the optical path they continuously rotated the direction of polarization of the incoming light. But they could not control for the optical activity that might be induced, for example, by a shift in the orientation of the copper oxide planes through the sample. In general, reflection experiments suffer from one ambiguity that does not trouble transmission experiments, and this ambiguity stems from several contributions to the reflected light intensity. Let  $A$  represent the amplitude for a reflection in which the direction of polarization relative to the  $z$  axis has not been changed (although the handedness of the light has been reversed), and let  $B$  represent the amplitude for a reflection in which the direction of polarization has changed. According to Halperin, in a system with time-reversal invariance,  $A_+ = A_-$ , where the subscripts indicate the relative polarization of the incoming light. However, in general, there is no such constraint on the  $B$  terms, and experimentally one cannot sort out whether one is measuring a difference between the  $A$ 's, which would definitely imply  $T$ -breaking, or between the  $B$ 's, which carries no such implication. Lyons told us he is conducting an experiment that would separate the  $A$  and  $B$  terms to provide an unambiguous answer to that question.

The Stanford experimenters also worked on a thin film of YBCO material, but they compared the polarizations of two light beams of the same handedness transmitted through the sample in opposite directions. This arrangement eliminates

Eventually the data turned out to nest for two limiting values of a then-unknown parameter,  $R$ . Later measurements of  $R$  refined a single universal curve for  $\nu W_2$ .

Because SLAC was and still is a unique accelerator, "we weren't under any competitive pressure," Kendall said. Data analysis was done independently on the West and East coasts. Theory, radiative correction formulas, computer programs and analysis were all done independently. The first results were reported by Friedman at the 14th International Conference on High-Energy Physics in August 1968. Panofsky, as a rapporteur at the meeting, diffidently raised the possibility of pointlike structure in the nucleon.

Once the data were taken at  $6^\circ$  and  $10^\circ$  angles with the 20-GeV spectrometer, Group A turned to the 8-GeV spectrometer to cover  $18^\circ$ ,  $26^\circ$  and  $34^\circ$ . The resulting data allowed them to determine the second structure function,  $W_1$ , which also was found to behave as a function of the single variable  $\omega$ —that is, to obey Bjorken scaling.

The experimenters waited for formal publication<sup>1</sup> until all the cross-checks were completed. The results

stand to this day, according to Kendall. Even when better radiative corrections were applied, the results changed by less than 1%.

Starting in 1970 the experimenters did similar scattering experiments with neutrons, interlacing an hour's run with hydrogen (protons) and an hour's run with deuterium (neutrons) to reduce systematic error.

## Feynman, partons and quarks

In 1968 Richard Feynman of Caltech had been thinking about hadrons as being made of smaller pieces he called "partons." When he visited SLAC in August of that year he was shown the inelastic scattering data, along with fits to the Bjorken scaling law. (See the article by Bjorken, "Feynman and Partons," in *PHYSICS TODAY*, February 1989, page 56.) Friedman reminisces: "Feynman came up with a simple dynamical model which experimenters could really understand. It was another way of saying what Bjorken was saying except it gave it a sort of physical structure." Feynman identified the scaling variable  $x = 1/\omega$  with the fraction of momentum the parton carried in a highly relativistic nucleon. If the partons were pointlike you'd get precisely this scaling.

He also showed that the structure function was related to the momentum distribution of the partons.

Friedman cites three reasons for the unpopularity of quarks at that time: They had not been seen. The fractional charge assignments appeared unreasonable. And since quarks had not been observed in cosmic rays, they were expected to be very heavy and accordingly to have very strong binding energy, suggesting a great difficulty in thinking of them as independent constituents.

Feynman's work greatly stimulated the theoretical community and a variety of theories emerged. After Curtis Callan and David Gross showed that a particular ratio  $R$  of  $W_1$  and  $W_2$  would be sensitive to parton spin, the SLAC-MIT group found that this ratio was consistent with partons with spin  $1/2$ , just as Gell-Mann had required for the quarks. That eliminated certain competing possibilities. Once the neutron data were analyzed<sup>2</sup> it became clear that the neutron yields differed from the proton yields, eliminating some other competing theories.

## Quarks are accepted

Within a year or so complementary measurements of neutrino inelastic scattering at CERN's Gargamelle heavy-liquid bubble chamber provided a powerful extension of the SLAC-MIT results. If one divided the SLAC deuterium results by  $5/18$  (the value obtained by taking the average of the squares of the quark charges, or  $1/2 [(-1/3)^2 + (2/3)^2]$ ) to account for the difference between the electromagnetic interaction between quark charges and the weak currents in neutrino interactions, "the neutrino data lay right smack on the SLAC results," according to Kendall. The neutrino and electron data taken as a whole gave very strong evidence that the constituents were quarks.

There followed deep inelastic muon scattering, electron-positron collisions and proton-antiproton collisions showing quark-quark interactions. Then hadron jets showed up.

It took several years for the community of physicists to accept quarks, largely because of the contradiction between their appearance as pointlike constituents and their very strong binding within hadrons. Even then, as Jarlskog said at the Nobel ceremony, "the results could not be entirely explained by quarks alone. The Nobel Prize-winning experiment indicated that the proton also contained electrically neutral constituents. These were soon found to be 'gluons,' particles gluing the quarks together in protons and other particles."

JOAN CARTIER



ALRIGHT RUTH, I ABOUT GOT THIS ONE RENORMALIZED.

wonders whether the ultrasonic anomaly indicates a subtle electronic phase transition at this temperature.

What is the resolution to the conflicting results so far reported? Many observers agree that both the experiments and their interpretations are very complex, and that great caution is required in evaluating them. More experiments are under way in all three camps that may clarify the situation. So far no samples have been exchanged, although all three groups seem to agree the idea makes sense.

If the experimental results stand as reported, what are the implications? One possibility for resolving the Stanford and Bell Labs results (but perhaps not the Dortmund measurements) is to postulate that the optical effects depend on the frequency of light. Another possibility is that the signals come from the *B* terms.

Surprisingly, in the year since the Bell Labs and Stanford groups first aired their results, only the Dortmund group has been heard from. Are others trying but being very cautious, or are the experiments simply too painstaking to undertake easily? Certainly the outcome is of great interest to the theorists, who are anxiously watching from the sidelines. Proponents of anyon superconductivity are expected to be disappointed—but not crushed—by a negative result: In the absence of well-defined quantitative predictions even that would not spell doom for anyone.

—BARBARA GOSS LEVI

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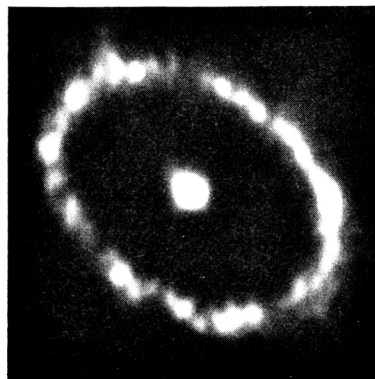
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## Ring Around 1987 Supernova Provides a New Yardstick

The picture at right shows a gaseous ring, 1.37 light-years in diameter, surrounding the remnant of supernova 1987A. This image, taken by the European Space Agency's Faint Object Camera aboard the Hubble Space Telescope, achieves a diffraction-limited resolution of 0.07 arcseconds, despite the Hubble's much lamented spherical aberration.

This unprecedented resolution, together with the International Ultraviolet Explorer satellite's continuous monitoring of the ring's waxing and waning luminosity in the years following the February 1987 supernova explosion, has provided astronomers with the most precise distance measurement yet achieved for an object outside our Galaxy. SN 1987A resides in the Large Magellanic Cloud, our neighbor minigalaxy. We now know, with an uncertainty of only  $\pm 5\%$ , that this 1987 supernova remnant is  $1.69 \times 10^5$  light years from us. Before the Hubble image, the uncertainty was  $\pm 12\%$ . Estimating the distance of remote extra-Galactic objects is a cumulative, bootstrap enterprise. Allan Sandage (Carnegie Institution) calls this new result "an important recalibration of the first step on the scale of intergalactic distances."

The ring, made of material ejected from the supernova's progenitor star in its red supergiant phase, already girdled the star five thousand years before it exploded. But it was cold and dark. Only when the radiation from the supernova blast reached the ring and heated it to  $2 \times 10^4$  K did it become observable to ultraviolet and

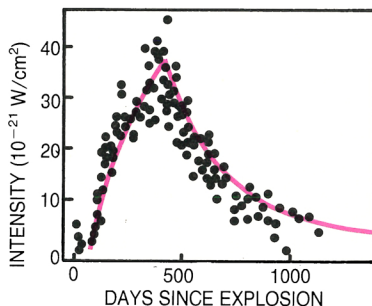


visible-light telescopes.

If the plane of the ring were normal to the line of sight, it would have been seen to light up all at once, some eight months after the supernova explosion. But because the ring is actually tilted by about  $45^\circ$  from the normal, different parts are at different distances from us. Its nearest point therefore appeared to light up after only three months, while the farthest point remained dark for about another year.

The time dependence of the ultraviolet radiation from the region around the supernova, monitored by the IUE satellite at the 1750-Å line of doubly ionized atomic nitrogen, is shown in the figure below. It peaks when the whole ring is finally seen to be lit up, some 420 days after the supernova explosion, and then it decays rapidly as the ring cools. The red curve is the best fit<sup>1</sup> of this scenario to the ultraviolet data, yielding a ring diameter of  $1.30 \times 10^{13}$  km and a tilt of  $43^\circ$ . The Hubble image tells us that the angular diameter of the ring is 1.66 arcseconds. It is this combination of an absolute, light-transit-time measurement with an angular size measurement of the same celestial object that yields an intergalactic distance determination of unique precision.

—BERTRAM SCHWARZSCHILD



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