search & discovery

Parity nonconservation in neutral-current interactions

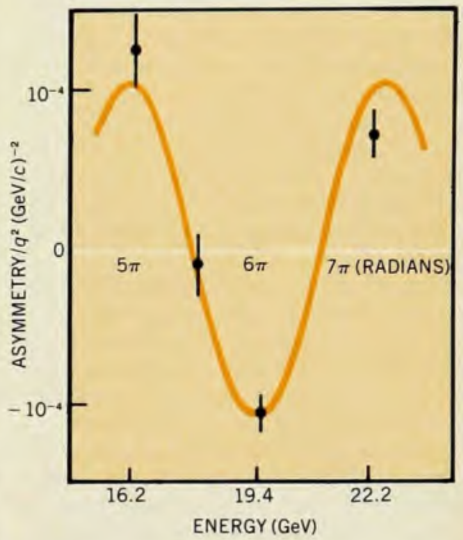
An experiment with polarized electrons at SLAC has found evidence for parity nonconservation in a neutral-current interaction. The observation offers strong support for the Weinberg–Salam gauge theory of the weak and electromagnetic interactions and removes the need for the more complicated gauge theories that have been developed since the original model by Steven Weinberg (Harvard University) and Abdus Salam (International Centre for Theoretical Physics) more than ten years ago.

Since particle physicists started taking the Weinberg–Salam model seriously, the model has had its ups and downs. Although its prediction of neutral currents was verified in 1973, since then various flies have appeared in the ointment, such as the so-called high-y anomaly and the failure to observe nonconservation of parity in atomic bismuth. More complicated gauge theories were developed to account for the experimental results. But the recent SLAC observation of nonconservation of parity in the inelastic scattering of polarized electrons from deuterium and hydrogen makes many particle physicists feel Nature is simple after all. As a noted theorist said, "The game isn't over, but it looks like the Weinberg–Salam model is a good approximation to the ultimate gauge theory."

The SLAC-Yale experiment was an extremely difficult one—looking for an interference between the weak and electromagnetic forces. Gauge theories predicted that the parity nonconserving asymmetry would be observable at the level of roughly one part in 10^4. And to see this effect, the experimenters had to measure the difference between the counting rate of electrons with one helicity and the counting rate of electrons with opposite helicity.

Results from the experiment have been eagerly awaited. They were announced by Charles Prescott at a regular Monday colloquium at SLAC on 12 June and at the Sixth Trieste Conference on Particle Physics later that month, and by Charles Sinclair at the Oxford Conference on Neutrino Physics early in July. A paper has been submitted[1] to *Physics Letters* by the 20-person team from SLAC, Yale University, CERN, Aachen and the University of Hamburg, which is led by Prescott, Sinclair, Richard Taylor (SLAC) and Vernon Hughes (Yale University).

The group used longitudinally polarized electrons from SLAC with energies between 16.2 and 22.2 GeV. Just as in the old inelastic-scattering experiments done at SLAC that provided support for the parton model, the experiment looked at



Observed asymmetry in SLAC experiment shows the expected cosine variation (colored curve) as the beam helicity changes as a function of beam energy owing to the $g-2$ precession in the beam transport system. The cosine behavior is taken as strong evidence that observed effects are caused by electron spin.

inelastically scattered electrons coming from an unpolarized deuterium target (and later an unpolarized hydrogen tar-

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Three groups see diamagnetic anomaly in copper chloride

A group of experimenters in Moscow has reported seeing very large diamagnetic signals from samples of copper chloride subjected to pressures of kilobars. The effect occurs at transition temperatures as high as 150 K. Two groups in the United States have seen related effects.

The Soviet group speculates that they have observed the Meissner effect or exclusion of magnetic flux characteristic of superconductivity. But they do not see perfect diamagnetism, and they do not see infinite conductivity. They do see an increase in conductivity four to six orders of magnitude, still small compared to that of ordinary metals.

Interest in the copper-chloride anomaly is reminiscent of that displayed five years ago when a group at the University of Pennsylvania reported seeing "superconducting fluctuations" in TTF-TCNQ at 60 K. Subsequent experiments failed to reproduce the magnitude of the effect originally measured.

Even though superconductivity close to room temperature in copper chloride is far from being demonstrated, many solid-state workers are wondering what could account for the observations. So far, except for superconductors, no substance has been observed with such a large diamagnetic susceptibility. And the highest superconducting transition temperature known is about 23 K. If copper chloride is not a superconductor, what is it?

The Moscow experiment, done by N. B. Brandt, S. V. Kuvshinnikov, A. P. Rusakov and V. M. Semenov of Moscow State University and the Moscow Institute of Steel and Alloys, was reported[1] in the Russian version of *JETP Letters* in January.

Earlier, in 1977, Rusakov collaborated on an experiment at Cleveland State University with C. W. Chu and S. Z. Huang (now at the University of Houston), Steven Early and Theodore Geballe (Stanford University) and C. Y. Huang (Los Alamos). The group observed similar anomalies but on a smaller scale; their results are reported[2] this month in *Physical Review B.*

And very recently, Issai Lefkowitz (Army Research Office and University of

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North Carolina), Philip Bloomfield and Joanne Manning (University of North Carolina), have also seen a similar anomaly. A paper describing the results has been submitted for publication.

All three experiments are quite similar. The copper-chloride crystal is heated to the melting point and then quenched to obtain the zinc-blende structure. To measure the differential magnetic susceptibility, two coils are used: One contains the copper chloride. The other contains a sample of lead or tin, which is used to calibrate the absolute value and sign of the susceptibility. The measuring coils are placed in a pressure chamber. Electrical conductivity is measured with the aid of two electrodes.

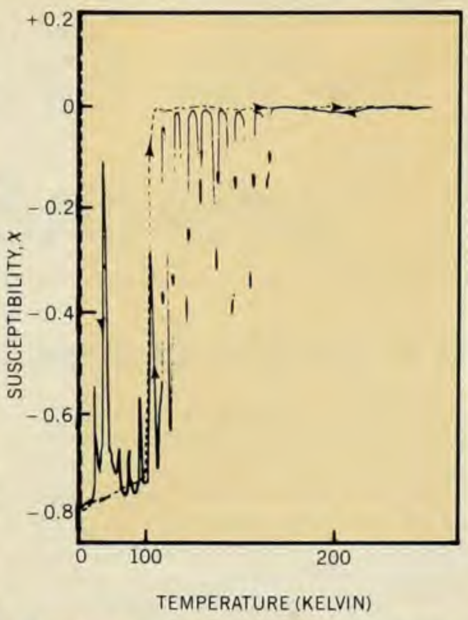
The Moscow experiment was done at 20 Hz, the Cleveland State one at 10 and 400 Hz, and the North Carolina one at 17 Hz. Lefkowitz noted that it is preferable to operate at low frequency to avoid induced currents.

Brandt and his collaborators observed unusual behavior when the sample was rapidly cooled (more than 20 deg/min) from room temperature. For samples at about 6-kilobar pressure and temperatures below 170 K, they found large increases in the ac diamagnetic susceptibility. While the sample was being cooled, they observed that the susceptibility, χ, oscillated almost periodically with temperature, changing repeatedly from the 10^{-6} range (cgs units), corresponding to weak diamagnetism, to values between 10^{-2}–10^{-1}. Their observed signal was 90% of the amount one would expect if the entire volume of the sample had become superconducting, corresponding to $\chi = \frac{1}{4}\pi$. At temperatures below about 100 K, the diamagnetic state became metastable, lasting for hours.

For samples that approached "ideal diamagnetism," the experimenters observed a simultaneous increase of electrical conductivity, which varied from sample to sample. In some samples, the conductivity increased by four to six orders of magnitude as the diamagnetism increased.

Chu and his collaborators last year observed a large diamagnetic shift in the susceptibility corresponding to 7% of the entire volume being superconducting. This occurred at temperatures between 90 and 250 K over ranges of 10–20 K when the samples were rapidly warmed (larger than 5 deg/min). At the same time, the conductivity increased by a factor of 40. Relative specific-heat measurements showed first-order transitions upon entering and leaving the strong diamagnetic state. To see the anomaly, it was essential to prepare the sample from the vapor.

This year, in May and June, Chu, Dale Harrison, Vic Diatschenko and S. Z. Huang (all at the University of Houston) repeated their earlier experiment, but with cooling rates of greater than 20 deg/min. They obtained roughly the same anomaly in susceptibility, failing to see the large diamagnetism reported by the Soviet group.



Anomaly in copper chloride shows in variation of magnetic susceptibility with temperature as sample is cooled (solid curve) and heated (dashed curve). At zero temperature is shown a calibration signal from the superconducting transition of a lead sensor. Pressure was roughly 5 kilobar. From Brandt *et al*, ref. 1.

Lefkowitz and his collaborators have made two susceptibility measurements. Anomalies occurred on warming to 150 K. over a range of ±(10–20) K. One measurement indicated that 8% of the sample volume was completely diamagnetic. The other measurement indicated that 50–125% of the sample volume was completely diamagnetic (greater than 100% because of the large error bars). In both cases, the sample was a transparent, amorphous solid with flecks of blue. The sample with the smaller anomaly was made by standard chemical techniques and that with the higher anomaly was prepared by chemical vapor transport.

Brandt and his collaborators think of their sample as being granular. They say in their paper, "It is natural to assume that the crowding out of the magnetic field from the sample and the simultaneous strong increase of the electrical conductivity of the sample are a consequence of the transition of the crystals into the superconducting state. It is most probable that it is the crystallites that make up the sample which go over into the superconducting state, while the intercrystallite boundaries, with the strongly disturbed structure, remain in the dielectric state." This causes the electrical conductivity to be finite and sample dependent and not necessarily a reliable indicator of the superconducting state, Geballe told us.

Chu and his collsborators note that high-temperature superconductivity in copper chloride has not been demonstrated conclusively. They suggest that if the diamagnetic anomaly can be stabilized by applying stress instead of rapid temperature change, it should be possible to do the magnetic-moment measurements in an applied field that would prove or disprove the existence of superconductivity.

Lefkowitz plans to use a SQUID device to make dc conductivity measurements. But Chu and his collaborators note that such measurements are likely to be less successful than static magnetic-moment measurements because less than 1 part in 10^6 of the normal high-resistivity copper chloride in the circuit path between the probes will limit observations of large conductivity increases.

Another puzzling feature in copper chloride is a sharp increase in conductivity (seven orders of magnitude) observed at higher pressures (40 kbar) and room temperature, found in 1975 by Rusakov, V. N. Laukhin and Yu. A. Lisovskii and by Chu, Early, Geballe, Rusakov and R. E. Schwall. This effect was observed only in samples prepared from vapor, but the relationship to the diamagnetic anomalies at lower pressure is not yet clear.

Very recently Earl Skelton (Naval Research Laboratory) and Ian Spain (University of Maryland) told us they have caused a transformation from the normally transparent copper-chloride crystal to a metastable form. They placed the sample in a diamond-anvil pressure cell (at 40 kbar) at room temperature, forming an opaque state. Then they cooled it to liquid-helium temperature. Upon warming to room temperature and returning the cell to atmospheric pressure, a given sample remained opaque for many days, in one case as long as a week. Without cryogenic cooling, the transition was immediately reversible on return to ambient pressure.

What is the explanation of the anomaly? Cuprous chloride is a semiconductor with a zinc-blende structure. The conventional picture of the band structure of copper chloride is that it has a direct gap at 3.2 eV and no indirect gap at lower energies. Rusakov and collaborators last year gave evidence for a strong indirect gap of about 0.32 eV (and a large effective mass ratio m_{hole}/m_e of about 100). Rusakov, Brandt and collaborators suggest excitonic superconductivity from small metastable regions or droplets of an electron–hole plasma.

Shortly after the Brandt experiments, two papers with further speculations were published in *JETP Letters*, 20 February, by B. A. Volkov, Vitaly Ginzburg and Yu. V. Kopaev (Lebedev Institute) and by Alexei Abrikosov (Landau Institute). Volkov and his collaborators, basing their work on the literature of the excitonic-insulator phenomenon, proposed a new effect that they called "superdiamagnetism." Abrikosov used a ten-year-old suggestion by Conyers Herring (Bell

Labs) that if one had an intrinsic semimetal in which electron mass and hole mass were sufficiently different and in which their concentrations were sufficiently low, there might appear a "Wigner lattice" of holes, permeated by the electron gas. Abrikosov then speculated that Cooper pairing of the electrons could be caused by their coupling to oscillations of the lattice of holes, with resultant superconductivity.

Very recently A. K. Rajagopal (IBM on leave from Louisiana State University) has argued that Abrikosov's calculations are in error because he fails to consider the effect of Coulomb repulsion of the electrons. Marvin Cohen and his collaborators at the University of California, Berkeley, have done a band-structure calculation that disagrees with the Rusakov model.

Several years ago David Allender, James Bray and John Bardeen (then all at the University of Illinois) developed a theory for excitonic superconductivity for a nonuniform medium consisting of layers or filaments of metal in a semiconductor matrix. Such a medium, they said, might show superconductivity. Geballe told us the copper-chloride anomaly might be due to a microscopic structural rearrangement and charge transfer resulting in fine-scaled conducting domains. This could allow, he believes, for some variant of the Allender–Bray–Bardeen mechanism to become operative. However, Bardeen himself told us he does not think the anomaly is due to the Allender, Bray and Bardeen mechanism. If the effect is real, he told us, he favors a mechanism involving electron–hole pairs, such as that advocated by Rusakov and Abrikosov. In any case, Bardeen thinks that the suggested explanation requires that the proposed "electron–hole" droplets in copper chloride have a much higher concentration of electrons and holes than those in silicon and germanium. The hole lattice, he said, would have to be incommensurate with a copper-chloride lattice and the holes not be self-trapped.

Lefkowitz told us that the mode instabilities (which depend on exciton density) are associated with high transition temperature superconductors. In some earlier experiments, in 1964–65, he had shown that a dielectric anomaly was only observable if one populated the solid (thallium chloride and thallium bromide) with excitons.

James C. Phillips and Eugene Blount (Bell Labs) are skeptical of excitonic superconductivity in copper chloride, noting that it requires a very small band gap between valence and conduction bands, inconsistent with the transparency of the material. They believe that the high electrical conductivity at high pressures may be the result of the reversible chemical reaction: 2 $CuCl \rightleftharpoons Cu + CuCl_2$. They do not offer an explanation of the high diamagnetism, but feel that the irreproducibility and peculiar temporal and temperature oscillations suggest that the ultimate explanation may lie in experimental artifacts.

Other explanations offered to us included piezoelectric charges, caused by squeezing the sample, hence leading to false pyroelectricity, or magnetic transformations.

Chu and Geballe stressed to us that the most important direction at present is to get the experiments under control. "We need better methods of sample preparation and characterization. Once definitive experiments have been done, the appropriate models are bound to follow."

—GBL

References

1. N. B. Brandt, S. V. Kuvshinnikov, A. P. Rusakov, V. M. Semenov, Pis'ma Zh. Eksp. Teor. Fiz. **27**, 37 (5 January 1978); Sov. Phys.–JETP Letters **27**, 33 (1978).
2. C. W. Chu, A. P. Rusakov, S. Huang, S. Early, T. H. Geballe, C. Y. Huang, Phys. Rev. B, to be published 1 September 1978.

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get). The experiment looks at electrons scattered at 4 deg from the beam and with secondary energy of 80% of the primary energy; the momentum transfer, q^2, varies from 1 to 1.8 $(GeV/c)^2$.

Between beam pulses the polarity of the next beam pulse is chosen in a completely random fashion. As Prescott explained to us, by randomizing the reversal one averages out effects produced by periodic fluctuations in the beam.

A new polarized-electron source was developed at SLAC for this experiment based on an approach suggested in 1974 by Edward Garwin (SLAC), Daniel Pierce and Hans-Christian Siegmann (ETH, Zurich). The new source differs in several respects from the atomic-beam source pioneered by the Yale group for use at SLAC in experiments using polarized beams and polarized targets at the same time. With this source, a Yale–SLAC group in 1976 achieved a sensitivity in the measurement of asymmetry of about one part in 10^3.

The new source consisted of a crystal of gallium arsenide that emits polarized electrons when bombarded with circularly polarized light. Large instantaneous currents are available from the source, up to 4×10^{11} electrons per pulse on target. (On occasion, the source produced more polarized electrons than could be accepted by the accelerator.) The average polarization was about 40%. By changing the circular polarization of the light hitting the gallium arsenide, the electron polarization can be reversed, and this change can be made easily and rapidly, with very little change in the properties of the electron beam.

Although the experiment requires an accuracy of 1 in 10^5 to see the predicted asymmetry, A, Prescott explained that the cross sections σ_+ for positive-helicity electrons and σ_- for negative-helicity electrons need not be measured that accurately. Because

$$A = (\sigma_+ - \sigma_-)/(\sigma_+ + \sigma_-)$$

lots of quantities cancel out.

The asymmetry the group finds for deuterium is $(-9.5 \pm 1.6) \times 10^{-5}q^2$ with statistical and systematic uncertainties each about 10%. For hydrogen, with fewer statistics, they find $A = (-9.7 \pm 2.7) \times 10^{-5}q^2$. With deuterium, Prescott noted, one would visualize scattering off six quarks, with equal numbers of up and down. With hydrogen, on the other hand, one has two up and one down quark. Although the asymmetry would be expected to be slightly different for hydrogen in the Weinberg–Salam model, the expected difference is much smaller than the experimental uncertainties.

Several consistency checks were made by the experimenters. For example, they made three different kinds of null measurements.

PETRA stored its first beam on 15 July, 6 months ahead of schedule. Gustav-Adolf Voss, project leader, is surrounded by team members celebrating in traditional fashion. Shortly after, a 3-mA beam of electrons was accumulated for two hours and 5-GeV electron–positron collisions were produced at low intensity. By mid-September, the PLUTO detector from DORIS is to be moved into the PETRA beam, and experiments with some luminosity are to begin at 5 GeV in each beam.