Particle Theory: Stanford Electron Experiment Closes Options

One of physicists' fondest dreams is to find a theory that explains the four basic forces of nature (gravitational, electromagnetic, weak, and strong nuclear) as different manifestations of the same underlying phenomenon. The closest theorists have come is a group of so-called unified gauge theories that unite the weak and electromagnetic forces. But enough experimental evidence to choose from among the various unified theories that have been proposed has been lacking, and the existing evidence is somewhat confusing. What has been called "just a gem of an experiment" at the Stanford Linear Accelerator Center (SLAC) is being hailed as a decisive turning point in choosing from among the options. Of the three main categories of theories, two seem ruled out. Moreover, the earliest and simplest of the unified gauge theories, introduced independently 10 years ago by Steven Weinberg of Harvard University and Abdus Salam of the International Center for Theoretical Physics in Trieste, seems to fit perfectly with the new experimental result.

The experiment, conducted by researchers from SLAC and Yale University under the leadership of Charles Prescott of SLAC, measured the difference in how strongly left- and right-handed electrons scatter off deuterium nuclei at high energies. Left- and right-handed refer to an electron's polarization or relative orientation of an electron's spin angular momentum and its direction of motion. Electrons are said to be polarized when most of the particles in a beam have their spin angular momenta pointing in the direction of motion (right-handed) or opposite to it (left-handed). The research team found a difference of 1 part in 5000, with an uncertainty of just under 1 part in 50,000, according to Richard Taylor of SLAC. It is the left-handed electrons that scatter more strongly.

The unified gauge theories involve quantized fields, including the familiar electromagnetic field. The quantum of the electromagnetic field is the photon, which, among its other roles, is the entity that carries the electromagnetic force between two interacting charged particles. In the theory of the weak force, which is the controlling influence in radioactive beta decay, there are three photonlike quanta that act as carriers of the weak force. Unlike photons, however, these quanta are heavy (current estimates are from 50 to 100 times the mass of a proton), and two of the three are electrically charged. The electromagnetic and weak forces are seen as unified in the sense that, at much higher energies than accessible in any accelerator today but comparable to particle energies in the early hot stages of the universe in a "big-bang" model, the two forces become comparable in their effects.

A triumph of the Weinberg-Salam version of unified gauge theory was the prediction of "neutral currents." Physicists use the term current to describe the flux of photonlike quanta that carry forces between particles. Before 1973, all weak force currents were charged—that is, they involved the electrically charged quanta of the weak force field. Neutral currents, involving the uncharged quanta predicted by the theory to exist, were found at the European Organization for Nuclear Research (CERN) and quickly confirmed at the Fermi National Accelerator Laboratory (Fermilab).

Subsequent detailed experiments of the same type, in which neutrinos bombarded nuclei, provided additional strong evidence for the theory and also nailed down the value of a free parameter that needed to be evaluated to make quantitative comparison between predicted and measured properties. But the neutrino experiments could not do everything. In particular, they have not been used successfully to demonstrate another predicted effect, parity nonconserving neutral currents. (Charged currents were known for many years to be parity nonconserving.) Parity refers to the effect on a particle reaction of inverting one or more coordinates. In the simplest case, parity is not conserved if the mirror image of a reaction occurs at a different rate.

Because left- and right-handed electrons are, in fact, mirror images of one another, the SLAC experiment conclusively showed for the first time that neutral currents do not conserve parity. Parity nonconservation was predicted by the Weinberg-Salam model, but not by some other unified gauge theories. The reason parity is not conserved is that, in the model, there is a part of the weak force that is felt only by left-handed particles. The effect is small because the weak force is weaker than the electromagnetic at the energy of the experiment. Moreover, the quantitative value of the effect agreed with that predicted when the value of the free parameter deduced from the neutrino experiments at CERN and Fermilab was used. Theorists say these results make the Weinberg-Salam model look very good right now.

One observer noted that the experiment came at a good time psychologically for particle physicists. Last year at the University of Washington and the University of Oxford optical physics experiments with bismuth vapor that were designed to search for parity nonconservation measured a null effect. Some particle physicists down-played the result, saying the theory for the complicated bismuth atom was not well enough worked out. A more recent experiment at the Institute of Nuclear Physics in Novosibirsk, also with bismuth vapor, contradicted the Washington and Oxford results and supported the Weinberg-Salam model. With the atomic physicists in disarray, the predisposition among the particle people is to consider the SLAC experiment definitive. James Bjorken, a SLAC theorist, cautions, however, that gauge theories are so elastic that a new, more complicated version could absorb both parity conservation for electrons in atoms and nonconservation for high-energy free electrons, if necessary.

Physicists consider the SLAC experiment "a thing of beauty." Beyond the already discussed significance, it provided the first experimental confirmation of neutral currents in electron-nuclear interactions; all previous demonstrations had involved collisions between neutrinos and nuclei. Despite its straightforwardness, the experiment was exceedingly difficult to carry out. Among the problems to be solved were monitoring the electron energy to 1 part in 10^6, positioning the beam at the target with an accuracy of a few micrometers, and constructing a strong source of polarized electrons. The source chosen was a crystal of gallium arsenide, a semiconductor. Circularly polarized laser light incident on the gallium arsenide caused photoemission of electrons from the crystal surface. Because of quantum mechanical selection rules, the electrons were themselves polarized. Electrons were produced at a rate of 120 pulses per second, each pulse having a randomly selected left- or right-handed polarization. The polarized electrons were then accelerated to an energy of about 20 GeV in the 2-mile-long linear accelerator at SLAC before crashing into the deuterium nuclei. Numerous checks were made to ensure that the observed effect was associated with the polarization of the electrons and was not an artifact associated with, for example, the electron source.—ARTHUR L. ROBINSON

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