Unified Gauge Theories: An Atomic Fly in the Ointment

In an age of specialization, what do elementary particle, nuclear, atomic, and astrophysicists have in common to talk about? One thing is the weak force, which is one of the four basic forces known in physics and the one responsible for such processes as beta decay of radioactive nuclei. The weak force also provides the only mechanism by which the notoriously hard to detect neutrino can interact with matter. Last month, experimental and theoretical physicists gathered at the Fermi National Accelerator Laboratory (Fermilab) in Batavia, Illinois for an unusual conference that brought together those normally isolated specialists to discuss the weak force.

The meeting was also unusual in that it was held as a memorial to Benjamin Lee, the late head of the theoretical physics department at Fermilab, who was killed in an auto accident early this summer. Lee was an active participant in the recent development of the theories, called gauge theories, which deal with the weak force; he was so highly regarded that the meeting attracted a star-studded cast of attendees, ranging from up-and-coming young prodigies, to established superstars, to aging partriarchs, not all of whom were invited as speakers.

Although Lee's presence was felt throughout the proceedings, the clearly evident theme was testing the gauge theories that began appearing 10 years ago with the aim of unifying the weak and electromagnetic forces under a single formalism. One of the fondest dreams of physicists is to devise a single theory to encompass all of the four basic forces (gravitational, weak, electromagnetic, and strong nuclear, in order of increasing strengths)—in effect, to explain the physical world. A step in this direction was taken a century ago when electricity and magnetism, once thought to be unrelated phenomena, were brought together in Maxwell's famous equations. Now the emphasis is on tying the weak and electromagnetic forces together, but there is a complication arising from the unlikely domain of atomic physics.

The complication is an effect with the formidable title of parity nonconservation in weak neutral currents. Parity refers to the effect of inverting the coordinates of a particle through the origin of its coordinate system ($x \rightarrow -x$, and so on). Parity is said to be conserved in elementary particle reactions, when the probability of the reaction is the same before and after such a coordinate inversion. In other words, when forces conserve parity no basic distinction between left and right exists. The weak force is the only one of the four forces that does not always conserve parity. There are two kinds of weak interactions, those involving a phenomenon called charged currents and those proceeding by way of neutral currents. It is the latter that are now of such concern to theorists working on unified gauge theories. In particular, according to the simplest theories, a small but measurable parity nonconserving effect should be seen when polarized laser light interacts with the atoms in certain metallic vapors, but so far, none is.

What has become known as the "standard" model for unified weak and electromagnetic forces is generally credited to Steven Weinberg of Harvard University, who outlined such a theory in 1967, and to Abdus Salam of the International Center for Theoretical Physics in Trieste, who reported similar concepts several months later. Important contributions were also made by Lee and by Gerard 't Hooft of the University of Utrecht. About 5 years ago, for example, 't Hooft showed how the theory could be cast into a form that was computationally tractable. As developed over the years, the unified theory was constructed somewhat by analogy with quantum electrodynamics. In the case of quantum electrodynamics, the force between electrically charged particles takes place through the exchange of photons, the massless and chargeless quanta of the electromagnetic field.

In the case of the weak force, the interaction also takes place by way of particles, but they are far from massless and may or may not be electrically charged. In the so-called Weinberg-Salam model, there are three such particles with masses 50 or more times that of the proton, one with a positive charge, one with a negative charge, and one neutral. Weak interactions involving the exchange of the charged particles, called intermediate vector bosons, are said to consist of charged currents, whereas neutral currents are observed when the neutral intermediate vector boson is exchanged. One of the great triumphs of gauge theories like the Weinberg-Salam model was the prediction of neutral currents, which were later reported by researchers at the European Organization for Nuclear Research (CERN) in 1973.

At the Fermilab meeting, researchers from the various fields of physics in which weak neutral currents could manifest themselves reported on the progress made in the last 4 years. Elementary particle physicists have found encouraging agreement between theory and experiments that deal with collisions between high energy neutrinos and nuclei in solid or liquid targets, and the data are now complete enough to discriminate between the Weinberg-Salam model and many, but not all, competing unified gauge theories. Weak neutral currents that do not conserve parity are expected to occur in nuclear transitions involving the emission of gamma-rays. But, participants agreed, neither are the experiments sensitive enough to measure the minute effect reliably nor is the theory of what the magnitude of the effect should be in hand. Astrophysicists pointed out that weak neutral currents could be large enough to determine the evolution of supernovae. But the physics of supernovae is so complex that, for the foreseeable future, the flow of information about weak neutral currents will be from the particle people to the astrophysicists and not vice versa.

The atomic physics experiments could not be so easily dismissed, however, and are now causing a lot of head-scratching among the theorists. Two experiments, in particular, are causing the consternation, one by a group at the University of Washington headed by Norval Fortson and the other by a University of Oxford group led by Patrick Sandars. Both groups measure the change in the direction of polarization of linearly polarized laser light as it passes through bismuth vapor, and both find that the change is at most ten times smaller than the Weinberg-Salam model predicts, although there remain some uncertainties traceable to the complexity of the bismuth atom, which contains 83 electrons.

The optical properties of atoms, which normally depend only on the interactions between the electrons of the atom and the photons in a light beam—that is, on the parity conserving electromagnetic force—would not seem to be a candidate for parity nonconservation. However, the electrons do spend enough time near the nucleus for the weak force to be manifested. Charged currents are ruled out, since the exchange of one electrical charge between the electrons and the nucleus would destroy the atom, but neutral currents are possible.

Because of these interactions, the quantum states of the electrons are altered in such a way that the plane of linearly polarized light is rotated slightly upon passing through a container filled with atomic vapor. If parity were conserved, there would be no rotation of the plane of polarization. (Optical rotation in atomic vapors is different from the familiar rotation of the plane of polarization by some organic and biomolecules, which is a geometrical effect.) The effect is measurable only when the frequency of the light is close to that needed to stimulate certain electronic transitions within the atom, and is generally expected to be larger for heavy atoms such as bismuth. Apart from details, the Washington and Oxford experiments differed mainly in that they dealt with transitions requiring different wavelengths of laser light. Early atomic calculations predicted rotations of the order of 10^{-7} radian for a vapor dense enough to absorb about one-half the light, whereas the observed rotations were consistent with 0 radian and had an error of about 10 percent of the predicted value.

Physicists began talking about these experiments more than a year and a half ago, but significant results were only published this summer. According to Fortson, further experimental improvement that will lower the uncertainty by a factor of 3 or 4 may be expected in the coming months. The greatest present uncertainties seem to be associated with the calculations that are used to predict the parity nonconserving contribution to the optical rotation. Theorists exploring the unified gauge theories, for example, view these questions as serious and think it premature to revise the Weinberg-Salam model solely on the existing evidence.

One difficulty with the calculations is that the atomic theory is based on the central field approximation, in which each electron has its orbit determined by a radial force directed toward the nucleus and formed as an effective average of all the forces on the electron due to the nucleus and all other electrons. But phenomena, such as the so-called many body effects in which two or more electrons act in concert, cast doubt on the accuracy of this approximation.

At the Fermilab meeting, Sandars reviewed the latest attempts by atomic physicists to upgrade the credibility of their calculations. One such attempt by Ernest Henley and Larry Wilets of the University of Washington in collaboration with Marcel Klapisch of the Hebrew University in Jerusalem considered some of these many body effects. The investigators found a negligible correction when only electrons with energies close to those involved in the bismuth transition were treated. A significant change was found by Sandars and his associates, who studied many body effects involving all the bismuth electrons. The Oxford group determined that the predicted optical rotation should be reduced to 0.55 its former value. A group at the Institute of Nuclear Physics in Novosibirsk, headed by I. B. Khriplovich, had earlier estimated the expected optical rotation from experimentally determined strengths of the relevant transitions. Their value is in agreement with the reduced optical rotation calculated at Oxford. As Sandars emphasized, however, this reduction still leaves a sizable discrepancy.

Other experimenters are looking for optical effects due to parity nonconservation in other atoms. The problem is to find a system that is computationally easier to deal with than bismuth but which still has a measurable effect. For example, M. A. Bouchiat, of the École Normale Supérieure in Paris, who together with C. C. Bouchiat first called attention to the advantages of using heavy atoms in parity nonconservation experiments, reported on attempts to observe circular dichroism of polarized laser light which is absorbed by a cesium vapor and reemitted at a longer wavelength. In circular dichroism, left and right circularly polarized light are absorbed unequally. A similar experiment with thallium vapor was reported by E. D. Commins of the University of California at Berkeley. But the experiments are not yet sensitive enough to measure an effect as small as that predicted.

Most of the enthusiasm for resolving the parity nonconservation problem was therefore reserved for two not yet performed experiments. One would involve atomic hydrogen, which has been treated in excruciating theoretical detail by now, but which presents some experimental problems. The other is not an atomic experiment at all. Researchers in an American-European collaboration at the Stanford Linear Accelerator Center plan to study what is called deep inelastic scattering of polarized electrons by protons. By polarized electrons is meant the condition when most of the electrons in the accelerator beam have their spin angular momenta aligned parallel or antiparallel to their direction of motion. The Weinberg-Salam model predicts that the probability of scattering for the antiparallel orientation differs from that for the parallel case by one part in 10^5. Weinberg told reporters after the meeting that the Stanford researchers can now detect scattering differences as small as 10^{-4}.

If it should turn out that parity is conserved in atoms (or if it is not conserved, but at a smaller level than predicted), the Weinberg-Salam model would have to be expanded but not necessarily discarded. Theorists would not be at a loss for how to go about this, and in fact many generalized theories have already been formulated. One class of such theories, called left-right symmetric theories, makes it possible to preserve the successful predictions of the Weinberg-Salam model in neutrino reactions but is flexible enough to allow for parity conservation in atoms. According to Jogesh Pati of the University of Maryland, who developed one of the symmetric theories with Salam 3 years ago, an additional motivation is that nature be intrinsically symmetric between left and right.

Parity nonconservation comes about in the gauge theories because the elementary particles around which they are constructed are conceived as being left- or right-handed, but only left-handed particles can interact by way of the weak force. Handedness is similar to the polarization already discussed. In the left-right symmetric models, both left- and right-handed particles can have weak interactions, but the cost is the introduction of three additional intermediate vector bosons, making a total of six.

Ultimately, the most dramatic test of the unified gauge theories will come with higher energy accelerators that can produce particles with masses of 50 to 100 billion electron volts (Gev). Then it will be possible to find the so-far unobserved intermediate vector bosons, whose masses vary from theory to theory. According to David Cline of the University of Wisconsin and chairman of the Fermilab meeting, such experiments may soon be possible. By 1981, for example, Fermilab may have expanded its facilities to permit experiments in which two counterrotating beams of protons and antiprotons with energies up to 1000 Gev each, collide head-on. And by 1984, Brookhaven National Laboratory may have its planned intersecting proton-proton storage rings in operation at energies up to 400 Gev, but with a thousand times higher collision rate.

The physicists' dream, however, was described by Sheldon Glashow of Harvard University in his review of ways to discriminate experimentally between competing theories. Electron-positron colliding beam storage rings are much more efficient than proton accelerators at producing new particles. In particular, Glashow noted, there should be an energy range between about 100 and 200 Gev in which new particles spew forth from the machine in wondrous profusion as from a cornucopia. Such a machine could cost $1 billion and have a circumference of 50 kilometers because it is much more difficult to accelerate electrons than protons to 100 Gev energies. European scientists are considering the possibility of such a machine, perhaps to be located at CERN, for startup around 1990.—Arthur L. Robinson