Neutral Currents: New Hope for a Unified Field Theory

Geneva, Switzerland. Progress in the construction of a huge new accelerator and a host of novel experimental results from existing machines are generating considerable enthusiasm among high energy physicists in Europe. The locus of most of the activity is the European Organization for Nuclear Research (CERN), one of the oldest and most successful trans-European institutions and a major factor in the emerging leadership of European scientists in many aspects of high energy physics (see box). Within the past year, for example, pioneering studies of proton-proton interactions with the unique Intersecting Storage Rings here have yielded surprising results concerning the reaction probability of these particles at very high energy and some intriguing hints about their structure. What is causing the most excitement among physicists both in Europe and in the United States, however, is the apparent discovery at CERN of a new elementary particle reaction that has profound consequences for theoretical physics.

The experiment in question was the product of collaboration on a scale large even by the standards of high energy physics, involving a team of more than 50 researchers from seven different centers (*1*). Their results, the experimenters believe, are strongly indicative of a phenomenon known as neutral currents. But other interpretations of the CERN results are also possible, and many physicists (including some on the experimental team) are maintaining a cautious attitude toward the findings. A few are frankly skeptical. Nonetheless, there is a growing conviction that neutral currents have indeed been discovered, and this view has received a boost from a second experiment just concluded at the National Accelerator Laboratory (NAL) near Batavia, Illinois, in which results consistent with the CERN findings were obtained.

The reluctance on the part of many physicists to go beyond a minimal interpretation of the experimental results derives in part from the revolutionary character of the neutral current phenomenon. Neutral currents are interactions between neutrinos and other particles which involve the exchange of an uncharged or neutral intermediary (the electric charge of the interacting particles does not change). Such a reaction is contrary to long held beliefs about the nature of the weak nuclear force, which controls neutrino interactions and such processes as radioactive decay.

According to the established theory, weak interactions always involve a transformation of electric charge for the leptons (electrons, muons, or neutrinos) in the reaction. Until the recent experiment, only such transformations were observed. But internal inconsistencies in the theory have in recent years led theorists to attempt to construct a more satisfactory version along the lines of the renormalizable, gauge invariant theory of electromagnetic interactions. Renormalizable here means that divergent terms in the theory, which would otherwise give rise to physically meaningless results under certain circumstances, can be removed, making the theory usable for predictive purposes. Recently G. 't Hooft of the

<u>*Speaking of Science*</u>

A Renaissance for European High Energy Physics:

Geneva, Switzerland. The attention of high energy physicists has in the past 2 years been focused on the experimental results obtained here at the European Organization for Nuclear Research (CERN) and elsewhere in Europe. The apparent discovery of neutral currents is but the latest in an enviable and growing list of European "firsts." Accustomed for many years to unquestioned leadership in high energy physics, U.S. scientists have not been slow to find an explanation for their declining fortunes—a lack of money. Having warned for several years that the cuts which have reduced funds for high energy physics by one-third since 1970 would hurt, many American physicists now feel justified in saying, in effect, "we told you so."

The view that a lag in U.S. funding has been translated into a lag in physics has been expressed by, among others, W. Panofsky, director of the Stanford Linear Accelerator Center (SLAC) and president-elect of the American Physical Society (*1*). Moreover, Panofsky believes that the U.S. system for administering research has lost all flexibility; the annual budget process and the attendant uncertainties force laboratories to live from year to year and make long-range planning or program shifts to exploit new ideas nearly impossible. In contrast, European high energy physics has in recent years benefited both from stable budgets and from more certain knowledge of what the fiscal future holds. At CERN, for example, a 4-year planning cycle is used despite the difficulties of meshing the budgetary processes of 12 different member countries. Firm budgets are adopted for 2 years in advance and provisional budgets that amount to informal commitments are agreed on for 2 more years.

The total amount of money available for high energy physics in the United States is now about $200 million, and in Europe the equivalent of about $330 million, at current exchange rates, is being spent yearly. But W. Jentschke, director-general of Laboratory I at CERN, believes that the rapid devaluation of the dollar has made it difficult to compare the relative strengths of the two research programs in terms of money alone. In an interview, he stressed that the United States has a large number of extremely good physicists and facilities that include what is still the largest accelerator in the world [at the National Accelerator Laboratory (NAL), Batavia, Illinois]. But he did not dispute Panofsky's main contentions. Jentschke's personal assessment, as he expressed

University of Utrecht, Netherlands, showed how this could be done for weak interaction theories.

The remarkable feature of these revised theories is that they treat weak and electromagnetic interactions as different aspects of the same process. Beginning with the work of S. Weinberg of Harvard University and A. Salam of the International Center for Theoretical Physics in Trieste, Italy, many such theoretical models of a unified weak and electromagnetic force have been postulated. All of these model theories find it necessary to assume the existence of neutral currents, or of new and heavier lepton particles, or both.

The exciting thing about the possible discovery of neutral currents is that they might be the first step toward confirming that the weak nuclear force is not fundamentally different from the Coulomb or electromagnetic force. The unification of electric and magnetic phenomena was one of the triumphs of 19th century physics, and the prospect that radioactivity is also an allied phenomenon is very alluring. Indeed, a unified field theory for all of the fundamental forces of nature has been a goal of theoreticians since early in this century—a goal which, since attempts are now going forward to incorporate the strong nuclear force in the same framework as the weak and electromagnetic forces, suddenly seems much closer. Against the background of these advances in theory, the discovery of a new neutrino effect which may be evidence for neutral currents is considered by many to be the most important experimental result of a decade.

The details of the CERN experiment are therefore of more than ordinary interest. The layout of the experiment was similar to that of virtually all high energy neutrino experiments. Protons accelerated to high energies [about 26 billion electron volts (Gev)] in the CERN synchrotron are directed onto a target of a material chosen to produce copious amounts of secondary particles, particularly pi mesons (π). The full intensity of the accelerator is utilized in order to obtain many secondary particles. The beam of secondary particles leaving the target is next focused with electromagnetic fields; the system used at CERN allows the experimenters to select either π^+ mesons, which decay to produce neutrinos, or π^- mesons, which decay into antineutrinos. The beam is then passed through shielding to absorb all particles except the weakly interacting neutrinos, which then pass on into a detector.

Neutrinos are extremely difficult to detect. In the conventional approach, one looks for a reaction in which a neutrino hits a nucleon and is transformed into a muon (or an electron, depending on the type of neutrino) which carries an electric charge. The neutrino itself has no charge and is so unreactive that only about one in 10^{11} undergoes a reaction within the 7 cubic meter visible volume of the CERN detector, a large bubble chamber known as Gargamelle. Whereas neutrinos leave no track, the resulting muons and other charged reaction products leave visible traces in the bubble chamber and are readily detectable. This transformation of a neutrino to a charged lepton also occurs in radioactive decay and was until recently considered an inherent consequence of interactions involving the weak nuclear force. What the CERN experimenters observed, however, was a large number of neutrino-induced reactions that did not produce an electron or a muon.

In analyzing 83,000 photographs taken in the bubble chamber while the neutrino (ν) beam was operating, the experimenters observed 102 events in which no muon or electron was detected (putative neutral current events), and 428 in which they were detected

United States Dominance a Thing of the Past

it to this reporter, is that "the technical facilities for high energy physics in Europe are very easily comparable to those in the United States, and the ability and spirit of our engineers and physicists are also not second to the United States."

Two examples of Europe's emerging leadership cited by physicists on both sides of the Atlantic are neutrino physics and the CERN Intersecting Storage Rings (ISR). In the United States, neutrino physics has been let slide somewhat, whereas CERN has invested heavily in the subject since the laboratory's beginning. Although the start-up of NAL is now rejuvenating neutrino physics in the United States, it is not surprising that the neutrino effect tentatively identified as neutral currents was first investigated in Europe.

An even more impressive example of pioneering, in retrospect, was the decision to build the ISR—a decision that was viewed skeptically by many physicists in the mid-1960's. A proposal to build a similar facility in the United States was rejected in favor of upgrading the existing accelerator at Brookhaven National Laboratory on Long Island, New York. In fact, CERN managed to upgrade its accelerator (comparable to that at Brookhaven) in addition to constructing the new machine, and the ISR has been so successful that the concept is now included among the future plans of virtually every high energy physics laboratory.

There are also some American success stories in recent years—important discoveries at SLAC and the completion of the 400-Gev accelerator at NAL ahead of the comparable machine now under construction at CERN. But there seems to be no question that, after 20 years of gradual development, high energy physics in Europe has come into its own, and has entered a period that a physicist at CERN describes as a renaissance both in spirit and in the breadth and depth of research activity. It is a view that is widely shared. Panofsky, who is spending a few months on sabbatical at CERN, told *Science* he is impressed by the style and quality of the work here. And, as another U.S. physicist somewhat ruefully described the situation, "Our day of preeminence is gone and we should take care that we don't fall behind."—ALLEN L. HAMMOND

Reference

1. W. K. H. Panofsky, *Phys. Today* (June 1973), p. 23.

(charged current events). In 207,000 photographs taken with the antineutrino ($\bar{\nu}$) beam operating, 64 neutral current events and 148 charged current events were seen. The conventional charged current reaction (Eq. 1) is well understood, but a considerable amount of searching for alternative explanations was necessary before a majority of the CERN experimenters were willing to assert that neutral current reactions (Eq. 2) had indeed been observed. The charged current interaction is

$$\nu + \text{nucleon} \rightarrow \mu^- + \text{hadrons} \quad (1)$$

and the neutral current interaction is

$$\nu + \text{nucleon} \rightarrow \nu + \text{hadrons} \quad (2)$$

where ν is a neutrino, μ^- is a muon, and hadrons are strongly interacting particles; similar reactions occur with antineutrinos.

One alternative explanation is that the reactions were due to background radiation consisting of neutrons or other neutral particles rather than neutrinos. Neutrons, originating in neutrino reactions in the shielding, do create an observable background in the bubble chamber. But neutrons are far more reactive than neutrinos, and the frequency of events due to neutrons would be expected to decrease in the chamber along the direction of the beam. Because of the size of the CERN chamber—it is nearly five times as long as the average flight path between reactions for neutrons of the energies involved—it was possible to study the spatial distribution of observed events. And instead of the nonmuonic events being concentrated at the front end of the chamber, they were distributed throughout the chamber in exactly the same manner as the charged current events. The distribution in energy and direction was also identical for both processes.

A correction for the neutron background was made on the basis of estimates of the number present. Monte-Carlo calculations (a technique for computer simulation in which a statistically random set of possible events is generated) of the number of neutrons that might be expected in the chamber indicated that 10 to 15 percent of the neutral current events could be explained as due to neutrons. These calculations are not unusual in particle physics experiments, and while they are not always accurate, they are in this case considered unlikely to be off by more than 50 percent. Because the neutron effect is a small one, the experimenters believe that the inaccuracy does not affect their conclusions. But the calculations do involve some assumptions about the probabilities of reactions and they represent the least certain link in the chain of evidence supporting the CERN findings.

Several other possibilities were checked as well. Neutral hadrons from the beam, if any, would be expected to produce as many or more events in the $\bar{\nu}$ run than in the ν run, but exactly the opposite asymmetry was observed. Cosmic rays were also found to be a negligible source of background. The experimenters concluded that unless some unknown particle with penetrating properties similar to a neutrino was responsible, their results indicate that neutral current reactions do occur.

The neutrino and antineutrino results can be regarded as two independent experiments, both of which seem to show that neutrinos can interact with or scatter off nucleons without changing. A third experiment suggests that a similar process happens when the target is an electron. In this case what would be observed is a single electron unaccompanied by other particles or reaction products. In more than 700,000 pictures from the bubble chamber, the CERN experimenters found one event that could unambiguously be identified as an isolated electron. Calculations similar to those done above indicate that the expected background from other reactions is small, however, and the experimenters conclude that the result, which they interpret as due to a neutral current reaction, is statistically significant.

One Model Can Fit All Results

The new CERN results—particularly the ratio of neutral current to charged current events—appear to be quantitatively consistent with the predictions of one theoretical model of weak and electromagnetic interactions. The Weinberg model, as revised by 't Hooft, gives specific estimates for the number of neutrino-electron interactions that should yield neutral current events. With the $\bar{\nu}$ beam intensities at CERN the estimate is 0.4 to 8.0 events, depending on the value chosen for one adjustable parameter in the theory—consistent with the experimental result of 1 event. For the more complicated neutrino-nucleon interaction the model predicts only the ratio of neutral current to charged current events, but again the CERN results are within the predicted range and are self consistent (one value of the chosen parameter fits all three experiments).

Credit for the first confirmation of the CERN results goes to a team working at NAL (*2*). Their neutrino experiment was conducted at higher energies and with a different setup than the CERN experiment. They used a large liquid scintillator followed by an array of counters and spark chambers instead of a bubble chamber as a detector, an arrangement which does not allow the details of the neutrino-induced reaction to be studied, but which produces results without the laborious analysis of photographs from a bubble chamber. The NAL setup also necessitates large corrections to the raw data, because the counters intersect only a fraction of the muons produced. Neutron background is not an important factor in the experiment, however. After correcting for the muons that escape undetected, the experimenters still found a number of events which they believe may well be neutral current reactions. The ratio of neutral current to charged current events was slightly higher, but consistent with, the CERN results. And because the NAL experiment is in many ways complementary to that at CERN, it reinforces the conviction that something new has been found.

Theoreticians emphasize that the results so far are not detailed enough to confirm or reject any particular model, although models which depend exclusively on heavy lepton pairs would seem to be contradicted by the data. But they believe that the discovery of neutral currents, and the remarkable and perhaps fortuitous agreement with a simple model, argues well for the unified weak-electromagnetic theory as a whole. And even though detailed interpretation is still to come, the CERN and NAL results have provided a real stimulus to efforts to work out more satisfactory theories and to explore further the connection between what were once thought to be two different fundamental forces.

—Allen L. Hammond

Notes

1. The CERN team included physicists from the Technische Hochschule, Aachen, Germany; the Université Libre, Brussels, Belgium; CERN, Geneva, Switzerland; Ecole Polytechnique, Paris, France; the University of Milan and the National Institute for Nuclear Research, Milan, Italy; the Linear Accelerator Laboratory, Orsay, France; and University College, London, England.
2. The NAL team included members from Harvard University, Cambridge, Massachuusetts; the University of Pennsylvania, Philadelphia; the University of Wisconsin, Madison; and NAL, Batavia, Illinois.