CERN Vector Boson Hunt Successful

Between them, two groups of physicists have collected 90 W's and 10 Z^0's whose properties fit the predictions of the electro-weak theory

UA-1 and UA-2 are code names for two groups of physicists at the European Laboratory for Particle Physics (CERN), together comprising almost 200 very happy researchers. From data collected in two 3-month-long runs last fall and spring, the groups have collected 100 intermediate vector bosons (90 W's and 10 Z^0's) whose properties so far fit the predictions of the unified quantum field theory of the electromagnetic and weak forces. Although the number of events is short of staggering, the discovery is immensely important. Physicists have been looking for the W for about 50 years. The Z^0 is crucial to the success of the method by which the two forces were melded into one—the electro-weak force.

Verifying the electro-weak theory, whose construction was largely accomplished during the 1960's, is hardly the whole story. Ultimately, physicists would like a master theory which generates from first principles and without any adjustable parameters the most elementary constituents of matter, and their properties, as well as the forces by which they interact. The currently venturesome and highly speculative notions of theorists toward this end build heavily on the foundation laid by the electroweak theory. Moreover, American physicists have just recommended to the Department of Energy that the United States aim at the quickest possible construction of an ultrahigh-energy accelerator (the Superconducting Super Collider or "Desertron" because only the desert would have enough room to hold it) costing $2 billion or more in order to test the newer ideas (*Science*, 22 July, p. 344).

The W and Z^0 experiments, in addition to their salutary effect on theory, have given a boost to the proponents of proton accelerators in the competition with those who favor electron machines. Some physicists had feared that the W and Z^0 might not stand out as clearly as they have against the complicated and intense background generated in the collisions between protons and antiprotons in CERN's accelerator, the Super Proton Synchrotron or SPS. The proposed American Superconducting Super Collider will smash protons against protons at energies 40 or more times as high as are now available at CERN.

The W and Z^0 are particles that carry the weak force, which governs many nuclear decay processes and all interactions involving neutrinos. In this way, they are similar to other vector bosons, such as the photon, which transmits the electromagnetic force between electrically charged particles, and the eight gluons, which are thought to be the bearers of the strong nuclear force that binds quarks together to make heavy elementary particles (hadrons) like the proton and pion. There are differences, however. The photon is massless and can exist as a free entity. The gluon is also massless but exists only in conglomerations with other gluons and with quarks. The W and Z^0 are extremely heavy, weighing in at over 80 and 90 times the mass of the proton, respectively. The mass explains why they have never been seen before; no accelerator before the SPS collider had enough energy to make them.

These particles obtain their mass by way of the unification process that ties the weak and electromagnetic forces together. The whole idea of unification thus depends first of all on the existence of the W and the Z^0 with the correct masses. Although they may uncover additional W events as analysis of the data continues, the UA-1 and UA-2 groups have so far reported the following (masses are expressed simply as GeV, following the equivalence of mass and energy in special relativity):

	UA-1	UA-2	Theory
W events	55	35	
W mass	81.0±2.0	81.0±2.5	83.0±3.0
Z^0 events	6	4	
Z^0 mass	95.2±2.5	91.2±0.9	93.8±2.5

The uncertainties listed are statistical. UA-2 has also given estimates of systematic uncertainties of ± 1.3 GeV and ± 1.7 GeV for the W and Z^0 masses. UA-1 has begun recalibrating its detector in order to look into this question.

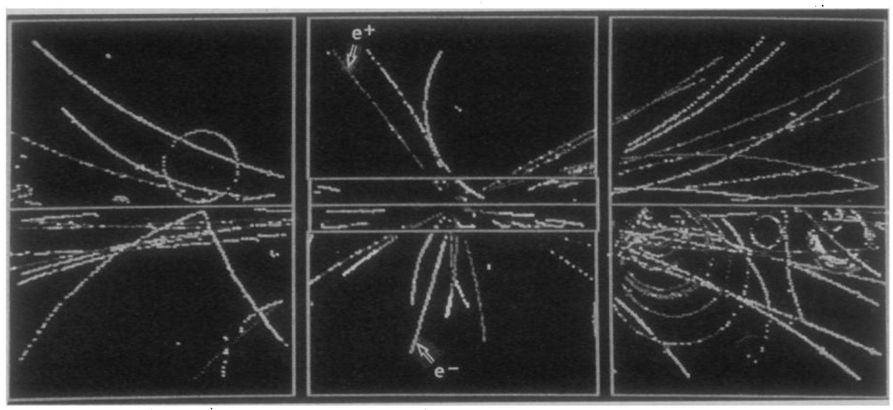
Even with the limited statistics, hardly anyone now thinks that the basic idea of unification is in question. "The masses look right on the button," says theorist Steven Weinberg of the University of Texas. Weinberg shared with Sheldon Glashow of Harvard University and Abdus Salam of Imperial College, London, the 1979 Nobel physics prize for his major role in developing the electroweak theory. Adds James Bjorken of the Fermi National Accelerator Laboratory, "alternatives are pretty much out, especially since the W mass fits so well."

Nonetheless, some caution is in order until more data and better statistics come in future experimental runs. William Marciano of Brookhaven National Laboratory calls attention to the larger than predicted difference between the masses of the W and the Z^0 in the UA-1 data. If this difference persists, and the error bars shrink, then the current electroweak theory would have to be modified. However, the large difference between the Z^0 masses obtained by UA-1 and UA-2 also means that one or both groups have not yet nailed down all their sources of error, so that such detailed speculation is premature.

Finding the W and the Z^0 has without doubt puffed up the pride of European physicists and deflated the egos of Americans by a comparable amount. The panel that recommended the Superconducting Super Collider to the United States clearly had in mind not getting scooped again. However, big prizes take big risks, and the normally cautious Europeans took an uncharacteristically large chance in gearing up for their vector boson hunt (*Science*, 10 July 1981, p. 191).

In 1978, CERN's directors approved a $100 million program to convert the SPS from a synchrotron, which produces a single beam of high-energy protons and directs them onto a stationary target, to a colliding-beam storage ring. In a storage ring, countercirculating beams of protons and antiprotons collide head on. The relatively inexpensive modification dramatically increased the effective collision (center of mass) energy available to create new particles from a little less than 30 GeV to 540 GeV.

Most observers credit Carlo Rubbia, a CERN physicist who is also a Harvard professor, with pushing the project through. He is well known to be energetic, persuasive, and an influential figure at the Geneva laboratory. Rubbia recently told *Science* that "the whole idea was to get in quickly and skim off the cream." The cream is finding the vector bosons. Detailed measurements of their myriad properties would be done by machines then on the drawing boards, an electron-positron collider at CERN with the name LEP that after some delay has now entered the construction phase, and a proton-proton collider to be built at Brookhaven. The same panel that last month recommended the Superconducting Super Collider also came down against completion of the half-finished Brookhaven machine. LEP is designed as a Z^0 factory and is to produce 10,000 to 100,000 of these per day. Brookhaven's collider would have generated up to 1 million W's per day.



CERN

The central part of the UA-1 detector images the trajectories of electrically charged particles in a magnetic field. The tracking chamber is a cylinder whose axis is the proton-antiproton beam. The collision point is the center of the chamber. The curvature of the tracks indicates the momenta of the particles. Particles with low momenta have tracks with large curvature. The two straight tracks marked e^+ and e^- belong to the very high energy and hence high momentum positron and electron from a Z^0 decay.

To skim the cream, there were the two large experiments, UA-1 and UA-2. There is nothing about the UA-1 detector that suggests getting in and out quickly. It weighs 2000 tons and cost $20 million. It was built over 3 years by one of the largest physics collaborations ever, headed by Rubbia, who had little trouble recruiting from CERN and around Europe with the W and the Z^0 as the prize. The group's paper announcing its Z^0 results was signed by 134 physicists.

UA-2 stands in almost complete contrast to UA-1, starting with its spokesman, Pierre Darriulat of CERN, who publicly is rather quiet and smokes his pipe a lot while listening to his colleagues. The UA-2 collaboration, with 60 members and its detector weighing about 200 tons, is more modest in scale than its UA-1 counterpart. The smaller size reflects a philosophical difference. UA-2 believes it is possible reliably to detect W's and Z^0's with a relatively specialized detector. The very powerful UA-1 instrument is firmly in the trend toward ever larger general-purpose detectors that have come to dominate colliding-beam experiments.

Having converted the SPS into a proton-antiproton collider and having constructed two large detectors, CERN was in mid-1981 the only laboratory in the world capable of making the vector boson search. In the United States, Fermilab had a proton-synchrotron similar to the SPS. The laboratory chose another route, however, and decided to build a second ring having double the energy of the old one with the aid of superconducting magnets. This facility is just now coming into operation for fixed-target experiments but will not be ready for colliding beams until an antiproton source is finished in about 2 years.

So, with the field to themselves, what did CERN physicists look for to verify that they had produced vector bosons? Being extremely unstable, W's and Z^0's do not live long enough to be observed directly, and therefore physicists have to rely on distinctive patterns of particles produced when they decay. Recall for the moment that the currently most elementary constituents of matter are the leptons (electron, muon, and tau with electrical charge −1 and their associated neutrinos with no charge) and the quarks (up, charm, and top with electrical charge +2/3 and down, strange, and bottom with charge −1/3). The Z^0, being electrically neutral, decays into a lepton-antilepton or quark-antiquark pair. For example, a Z^0 could decay into an electron and a positron with each having an energy about equal to one-half the Z^0 mass and flying apart back to back.

The W actually refers to two particles, the W^+ and its antiparticle the W^-. Because of the nonzero electrical charge that must be conserved in the decay, the lepton and the antilepton (or quark and antiquark) that are produced must have charges that add up to ± 1. A W^+ could, for example, decay to a positron and an electron neutrino, whereas the corresponding products of a W^- decay would be an electron and an electron antineutrino. Because neutrinos cannot be detected, the signal for a W decay would be a single electron of energy about half of the W mass and a "missing energy" due to the undetected neutrino.

Unfortunately, in the first full run in the fall of 1981 the SPS collider did not provide many events to study because of problems in getting an intense enough beam of antiprotons (*Science*, 21 May 1982, p. 836). A run scheduled for the following spring was delayed 6 months after an accident in the UA-1 detector temporarily disabled it. Referring to the delay and to plans being discussed to upgrade the UA-1 detector and improve the antiproton source, which would take time to implement, a visiting American physicist at CERN commented, "Carlo [Rubbia] may succeed in snatching defeat from the jaws of victory."

Physicists measure the performance of colliders by a parameter they call the luminosity. The number of events per second of a given type is the product of the luminosity and the cross section for the event to occur during a collision. The integrated luminosity for an entire experimental run measures the total number of events that could be observed. In the fall 1982 run, the collider was still far below the design specifications but nonetheless produced a respectable integrated luminosity of 25 inverse nanobarns, which is another way of saying that an event having a cross section of 1 nanobarn (1 barn = 10^{-24} cm^2) should have occurred 25 times. The cross section for a W with subsequent decay to an electron or positron and a neutrino is about 1/3 nanobarn and for a Z^0 decaying to an electron and a positron about one-tenth of that.

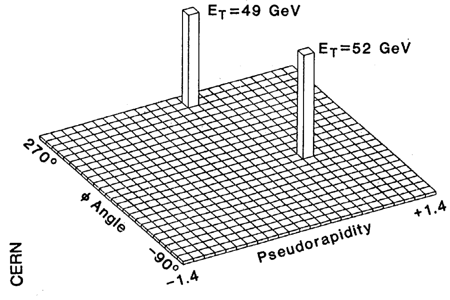
UA-1 recorded about 18 inverse nanobarns of the total integrated luminosity and should therefore have seen about six W's. At the end of the run last December, rumors flew immediately that W candidates were in hand. The "candidates" consisted of events with a single high-energy electron and a narrow jet of hadrons (pions and so forth). These turned out not to be W's at all. In fact, most have now been attributed to production and decay of bottom-antibottom quark pairs. By the end of January, however, both UA-1 and UA-2 announced more substantial results. UA-1 had six candidates and UA-2 had four candidates (all with an electron or positron and missing energy).

The most recent run, which ended on 4 July, saw a further marked improvement in the SPS collider performance, with an integrated luminosity of 137 inverse nanobarns. It could have been much more. At a summer school on high-energy accelerators at Brookhaven last month, CERN's Director General Herwig Schopper reviewed the collider operation. It was not until midway through the run that the SPS operators routinely achieved high luminosities. Then an unfortunate series of thunderstorms toward the end of June knocked out power. It takes about 24 hours to build up an antiproton beam, so even a short loss of power means a long delay in experiments. "In the last 3-month run, we got half our luminosity in 2 weeks," noted Darriulat in a telephone interview.

Nonetheless, there was more than enough data to locate the Z^0, which had escaped detection in the previous run. The first hints of this fervently sought particle surfaced in May, when Rubbia mentioned a single candidate event during talks on a visit to the United States. A month later, UA-1 formally staked a claim, when it announced five Z^0 events. UA-2 waited until 15 July to announce its four Z^0 candidates at a CERN seminar. It also discussed four other electron-positron events that did not quite pass all the tests, but "It's hard to imagine what else they could be," says Darriulat.

It is possible that the data already gathered contains another treasure, the top quark, which so far is only a hypothetical entity. Top quarks could be produced as top-antitop pairs in proton-antiproton collisions. A much more likely process, however, is the decay of W's to make these particles. A W^+ would go to a top-antibottom pair, whereas a W^- would decay to an antitop-bottom pair. The top would then decay part of the time to an electron (or a muon or a tau), a neutrino, and another quark. Since quarks, like gluons, are not allowed to exist as free particles, this quark would transform into a hadron jet. As in the direct decay of a W to an electron and neutrino, the electron from the top would have much higher than normal energy and so should be detectable.

While a number of factors make the reconstruction of top events trickier than that of W events, there have been persistent rumors that top candidates have already been found at CERN. Rubbia, who summarized the UA-1 data at the Brookhaven summer school, refused to answer a question from the floor about the top quark. Darriulat suggests UA-2 may have something to say in a month or two.



Z^0 signature

The second layer of the UA-1 detector measures the energy deposited by electrons and photons (electromagnetic calorimeter). The figure dramatically shows the very high energy positron and electron towering above a low-energy background. The particles are also 180 degrees apart in the direction normal to the proton-antiproton beam, as measured by the difference in their azimuthal angle φ. Finally, the coordinates of both peaks match the tracks in the central chamber. Pseudorapidity is a measure of the angle of the particle trajectory with respect to the beam axis.

Confidence in the existence of the top quark follows from the electro-weak theory which has quarks coming in pairs. The theory does not say how many pairs there are. Interestingly, astrophysical evidence implies that there are at most four and more likely just three types of neutrinos. The tie-in is that, at least so far, for each quark pair there is a lepton pair (electron-electron neutrino, for example). So, the number of neutrinos sets the number of quark pairs.

An accurate measurement of the "width" of the Z^0 could provide a firmer number. The Z^0 is a resonance and width accordingly refers to the range of energies over which it occurs. More neutrinos provide more ways for the Z^0 to decay, which widens the resonance. The already gathered data limits the number to less than about 20 to 30, according to Marciano. Most likely, LEP or a machine being developed at the Stanford Linear Accelerator Center (the linear collider), which will also be a Z^0 factory, will be required for a high-resolution experiment.

A Z^0 mass measurement of very high accuracy (0.5 percent or better) could also shed light on what Weinberg calls "the biggest question that is likely to be settled by experiment in the next decade." The question concerns exactly how the electromagnetic and weak forces are unified. Actually, theorists look at it from the other side. At very high energies (as existed in the first instants of the universe when it was enormously hot), the two forces are indistinguishable. So, how do they become different, or how does the symmetry between them become broken?

The electro-weak theory is one of a general class of quantum field theories called gauge theories. Whenever a symmetry is broken in gauge theories, particles called Goldstone bosons (after Jeffrey Goldstone of the Massachusetts Institute of Technology) arise. Weinberg's fundamental question is: Are Goldstone bosons elementary or composite particles? In the standard electro-weak theory, there are four "would-be" elementary Goldstone bosons. But, after some quantum mechanical transformations by way of the Higgs (after Peter Higgs of the University of Edinburgh) mechanism, there is left a single physical particle, the Higgs. The other bosons become absorbed into the W and Z and help give them their mass. Unfortunately, the theory gives scant guide as to the mass expected for the Higgs, which is also electrically neutral.

If the Goldstone bosons are composites, there must be elementary particles of a type not yet detected. For example, in the late 1970's Weinberg and Leonard Susskind of Stanford independently devised so-called technicolor theories. Technicolor refers to a new very strong force that binds together new particles called techniquarks into physically observable particles, including technihadrons with masses of order 1000 GeV and pseudo-Goldstone bosons with masses considerably less. Technicolor and related theories are just one subset of the venturesome new ideas that the proposed U.S. Superconducting Super Collider could investigate. The expectation is that many of the new particles would be so heavy that even the CERN collider could not produce them, although Fermilab's 2000-GeV collider may get a peek when it starts up.

In the meantime, says Weinberg, an accurate Z^0 mass determination would provide a clue as to which of the two types of symmetry breaking was the correct one because the predicted Z^0 mass is slightly different in each case.

As for CERN, there will be a long hiatus until September 1984 before the next collider run. During this time, the SPS will operate in its fixed-target mode to accommodate the large number of physicists who do this type of experiment, roughly 1100 as compared to 250 in the five collider groups. But a fascinating question has already surfaced. Given the spectacular success of the SPS collider, might it not be wise to convert LEP into a 10,000- to 20,000-GeV proton-antiproton collider at the earliest possible moment and thus steal the march on the Americans one more time?

—**ARTHUR L. ROBINSON**