Catching Some Zs

by David Hitlin and Rafe Schindler

EVER SINCE EMPEDOCLES in the 5th century BC classified the interactions between bodies, which he thought propagated by means of different effluences emanating from them, physicists have dealt with the fundamental phenomena of nature as if they were distinct. Modern physics has narrowed these phenomena down to four forces of varying strength and dependence on distance: electromagnetism, the strong and weak nuclear forces, and gravity. With the advent in the past decade of so-called Grand Unified Theories (GUTs), it has now become possible to contemplate a common origin for the first three of these forces. More speculative supergravity theories have also recently been advanced (*E&S* September 1985), which may lead to the eventual unification of all four types of interactions.

The search for experimental support for GUTs is one of the most exciting topics in elementary particle physics. As yet there is no direct experimental evidence to support the idea, but the attractiveness of the goal is seductive, and the search continues. A step below the GUTs is the theory based on the Lie groups SU(2) × U(1), which unifies the electromagnetic and weak interactions. This theory has already produced two Nobel Prizes — to Glashow, Salam, and Weinberg in 1979 for the theoretical work and to Rubbia and van der Meer in 1984 for the experimental demonstration of the existence of the fundamental gauge bosons of the theory — the charged W bosons and the neutral Z boson. Together with the photon, these particles are the carriers of the unified weak and electromagnetic force.

Even before observation of the W and Z particles, experimental support for this theory was impressive. Many phenomena, from parity violation in atomic systems to the scattering of high energy polarized electrons and neutrinos, are elegantly and consistently explained in this picture. Nonetheless, the actual production of the gauge bosons in high energy proton-antiproton collisions at the CERN laboratory in Geneva, Switzerland, in 1983 was greeted with enormous interest throughout the high energy physics community. Only a handful of Ws and Zs have so far been produced in this way, but this explicit demonstration of their existence has substantially bolstered confidence in the validity of the concept of a unified weak and electromagnetic force.

There is another way to produce W and Z particles, one that promises to yield vastly larger samples for study. This method is called electron (e^-)-positron (e^+) annihilation. The e^+e^- technique has produced a number of dramatic discoveries in the past, notably that of the psi meson and its relatives, which were found at the small SPEAR storage ring at the Stanford Linear Accelerator Center in 1974. The SPEAR machine is still generating exciting results; the current Mark III experiment, with which we are both associated, has been in the forefront of searches for exotic new elementary particles and in the study of the decay properties of charmed mesons.

The technique used in electron-positron storage rings is conceptually simple, but difficult to execute. A ring of magnets guides bunches of electrons and positrons (the antiparticle relative of electrons) in a circular orbit. Since the electrons and positrons have opposite electric charge, the same magnetic field can serve to guide them in circular orbits in opposite directions. At two or more points, called interaction regions, the electrons and positrons are brought into collision (hence the name "colliding beam accelerator"). In the collision the electrons and positrons may annihilate, forming a short-lived state with an energy that is the sum of energies of the electron and positron. This short-lived state then decays into a variety of elementary particles.

A typical experiment occupying one of the interaction regions of the storage ring consists of an apparatus that has the capability of identifying the types of particles produced in

Leptons — a family of elementary particles having no known substructure and participating in electromagnetic, weak (and gravitational) interactions.

Hadrons — the largest family of elementary particles (several hundred are known). Hadrons are composed of a quark-antiquark pair (mesons) or three quarks (baryons); they participate in all known interactions.

Quarks — the elementary constituents of hadrons. Five "flavors" (up, down, strange, charmed, and bottom) have been experimentally confirmed. A sixth, the top quark, is thought to exist, but experimental evidence for it is controversial.

Gauge bosons — the carriers of the forces between elementary particles. The unified electroweak force is carried by the massless photon, two heavy charged bosons (W^+ and W^-) and the heavy neutral Z^0. The strong force is carried by gluons.

Positron — the antiparticle of the electron. It is identical to the electron except for the sign of its electric charge and its lepton quantum number.

Muon — another lepton, 207 times the mass of the electron. It is unstable, decaying with a mean lifetime of 2.2 microseconds.

Neutrino — a neutral, very light (or massless) lepton that interacts only through the weak force. The neutrino interacts so weakly that its typical mean free path is 100 light years of water.

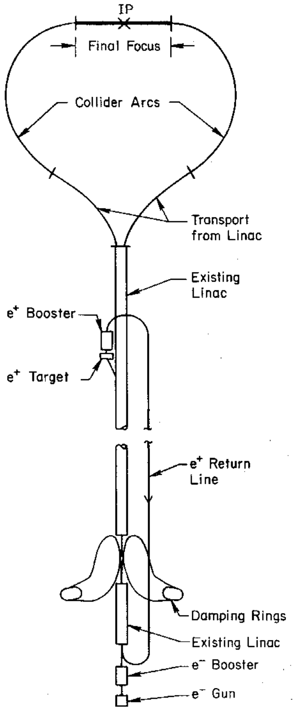
Pi meson — the lightest meson composed of one quark and one antiquark of the two lightest quark species, usually called up and down. It is the most commonly produced secondary particle in elementary particle interactions.

K meson — the lightest meson that contains a "strange" quark; it has 3.5 times the mass of the pi meson.

Psi meson — a bound atomic system composed of a charmed quark and an anti-charmed quark. It is most easily seen in electron-positron annihilation at a mass of 3.1 GeV as a spectacularly prominent narrow enhancement in the annihilation cross-section.

Upsilon meson — a bound atomic system of the next heaviest quark and antiquark, the bottom quark.

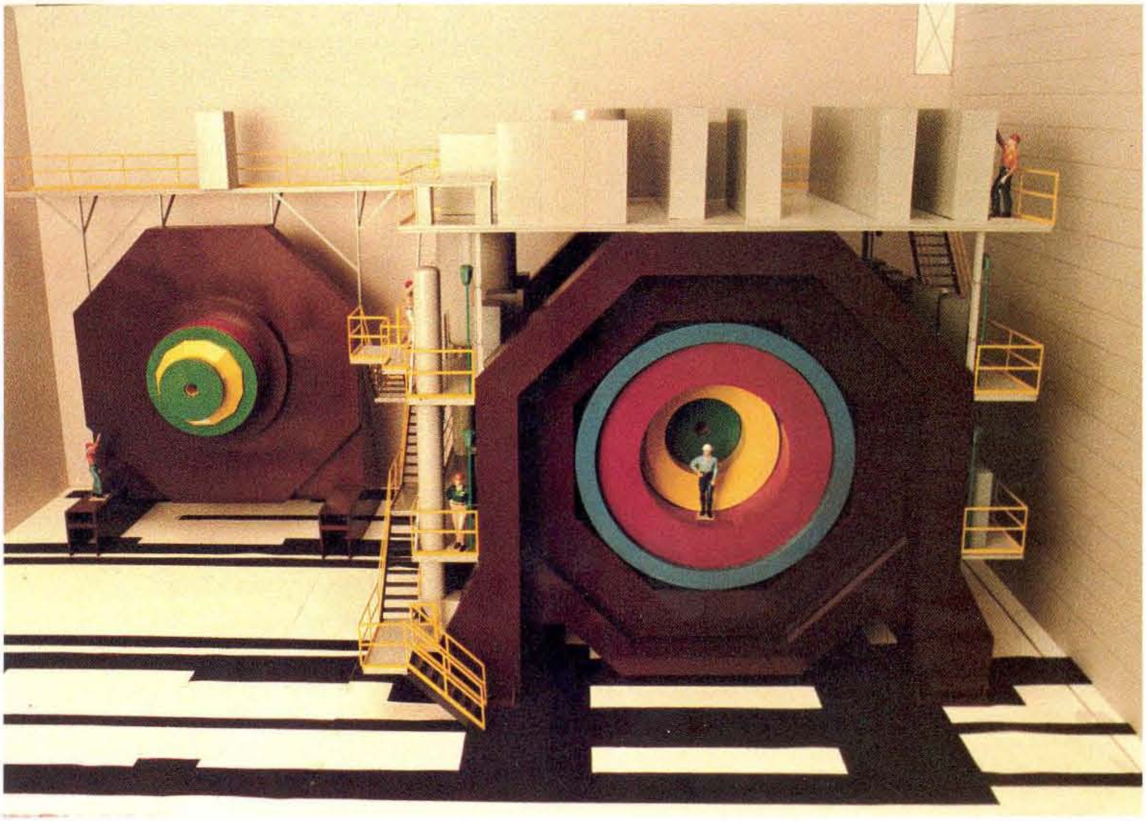
Supersymmetric particles — a class of new particles related to known particles in supersymmetric theories, a type of GUT. Each known particle has a supersymmetric partner in this scheme. Thus the photino is the partner of the photon, the gluino is the partner of the gluon, etc. Many of these supersymmetric particles interact weakly and so must be searched for by "missing energy" signatures.



The layout of the SLC is shown above. The e^+e^- beams from the existing two-mile linear accelerator (Linac) are introduced into the collider arcs and brought into collision at the interaction point (IP).

the annihilation and of measuring their directions and energies. The final states so produced are examined for evidence of new states of matter or are used as a particularly clean source to study the detailed properties of already known particles. One of the most interesting phenomena seen in the final states produced in e^+e^- annihilation are resonances. When the available energy (that is, the sum of the electron and positron energies) corresponds to the mass of certain new particles, there is a spectacular increase in the reaction rate. The psi meson was discovered in just this way. As the beam energies were tuned in very small steps, an unexpected increase of the number of interactions by a factor of a thousand occurred within a small energy region. The psi turned out to be a bound state of a new quark and antiquark, in this case the charmed quark. A few years later another resonance of this kind, called the upsilon (a bound state of the next heavier quark, the bottom quark) was found in a fixed-target experiment at Fermilab in Illinois and subsequently produced via e^+e^- annihilation.

Physicists expect that the most spectacular resonance of all — an increase of several thousand in the reaction rate — awaits them if they can build electron-positron colliders that can produce the mass of the Z^0 particle. The Z^0 is, however, 30 times more massive than the psi and 10 times more massive than the upsilon and will require large new accelerators to produce this much energy in electron-positron collisions. The obvious approach to the problem is to build a storage ring, such as the LEP machine under construction at CERN, of sufficient energy to reach the Z^0 regime. But this technique faces a problem intrinsic to the nature of electrons and positrons themselves. When light charged particles are accelerated (circular motion is continuous acceleration), they radiate electromagnetic energy, typically in the form of x-rays. This synchrotron radiation is an enormous technical problem; the radiated energy heats the vacuum pipe in which the electrons and positrons are circulating, necessitating elaborate cooling systems to remove the heat. Furthermore, the energy lost to radiation must be continuously restored to the beam. Since the synchrotron radiation loss increases rapidly with acceleration, gentle bends are required, and very large machines are the result. CERN's LEP storage ring, 27 kilometers in circumference, is generally felt to have reached the practical limit of this approach. Since electron-positron annihilation has been extraordinarily successful in exploring new physics at high energy, the abandonment of the technique due to the



In this scale model of the SLD detector the main body of the detector stands at right, and one of the two doors that close off the ends is on the left. The red cylinder is the barrel of the liquid argon calorimeter; the red of this calorimeter can also be seen in the end cap at left. The blue cylinder is the solenoidal coil that provides the magnetic field. Green represents the drift chambers that serve to track particles, while the yellow sections are the Cerenkov Ring Imaging Devices for particle identification. The large brown structure is the iron flux return for the magnet.

limitations of storage ring economics is not a happy prospect.

But there is a possible solution to the problem. Since the continuous repetitive acceleration due to circular motion is the source of the difficulty, it is tempting to think of an accelerator design that avoids this motion and the inevitable synchrotron radiation. Conventional electron accelerators, those whose beam is eventually delivered to a stationary laboratory target, have long been built as one-pass, straight-line devices — linear accelerators.

The two-mile linear accelerator at the Stanford Linear Accelerator Center (SLAC) is the largest machine of this type. Now nearly two decades old, it has had an illustrious history, serving both as a conventional accelerator and as a means of injecting electrons and positrons into the two SLAC e^+e^- storage rings, SPEAR and PEP. The two-mile accelerator is currently being converted into a new type of colliding beam machine called a linear collider (the SLC), in which electrons and positrons are produced, accelerated to high energy, and then introduced into circular arcs through which they travel only once, colliding at the interaction region. The repetition rate of the SLAC accelerator is 180 hertz, so there are only 180 opportunities per second for the electrons and positrons to interact, compared to the 45,000 opportunities per second at the LEP accelerator.

The measure of the brightness of the source in colliding beam accelerators is called luminosity. Since the luminosity clearly depends on the number of electron-positron crossings per unit time, the SLC is at a competitive disadvantage. The luminosity also depends on the current density in each beam, however, and it turns out to be possible to increase the current density in a linear collider over that in a storage ring by a large enough factor to achieve comparable luminosity. In the SLC this is done by having a large number of particles — as many as 10 billion electrons or positrons — in each accelerated bunch, and by making the transverse size of the beam bunches very small — a few microns in diameter. Techniques for achieving these very high currents and very small beam sizes have already been successfully demonstrated.

It thus appears possible to convert the existing accelerator into a linear collider with performance in the center of the mass energy regime of the Z^0, which is competitive with that of the LEP storage ring. This is an exciting prospect for several reasons: first, it can be done quickly, so that Z^0 studies at SLAC can begin several years before LEP is completed in 1989 or 1990; and second, the SLC can be viewed as a prototype of much larger linear colliders, which can extend the electron-positron annihilation technique to even higher energies where storage rings are economically impractical.

When the SLC begins to deliver beams for physics experiments in 1987, only one detecting device will be able to use the beam at any given time. The first such detector will be the Mark II, a device originally commissioned at SPEAR in 1978 and then moved to PEP. The Mark II is currently undergoing extensive revisions to enable it to cope with the more difficult experimental demands of the Z^0 energy region. Caltech is participating in this upgrade of the Mark II and will engage in the initial experimental phase of the SLC.

At the same time construction of a new detector, the SLD, which is specifically designed for Z^0 detection, has begun as a collaboration among several universities, including our Caltech group. The SLD is a much larger and more ambitious device, comparable to detectors planned for LEP. It will share beam time with the Mark II beginning in 1988 or 1989, ultimately supplanting it. The greater experimental capabilities of the SLD will be crucial in many of the most exciting experiments to be performed on the Z^0.

The Z^0 exists for only 10^{-24} seconds before it decays; we can investigate it only through the products of its decay. Since the decay of the Z^0 results in final states with many more particles having higher energies than previously produced in electron-positron collisions, this new generation of detectors will confront an unprecedentedly difficult experimental situation. The SLD detector is designed to cope with Z^0 decays through a variety of sophisticated subsystems. Measurement of charged particle momenta is accomplished by recording the radius of curvature of the particles in a 0.6 tesla solenoidal magnetic field by means of a large drift chamber, which measures position along particle tracks to an accuracy of better than 100 microns. Charged particle identification, that is, the classification of final state tracks as pi mesons, K mesons, protons, and so on, will be done with a Cerenkov Ring Imaging Device (CRID), which detects the angle at which Cerenkov light (a shock wave analogous to a sonic boom) is emitted when the particles pass through layers of carefully chosen gas and liquid. The largest detecting element of the SLD will be its calorimeter, which consists of two parts: a liquid argon calorimeter and an iron calorimeter which is integrated with the magnet flux return. Management of the design and construction of the liquid argon calorimeter, perhaps the most important single component and a $13 million undertaking, is centered at Caltech.

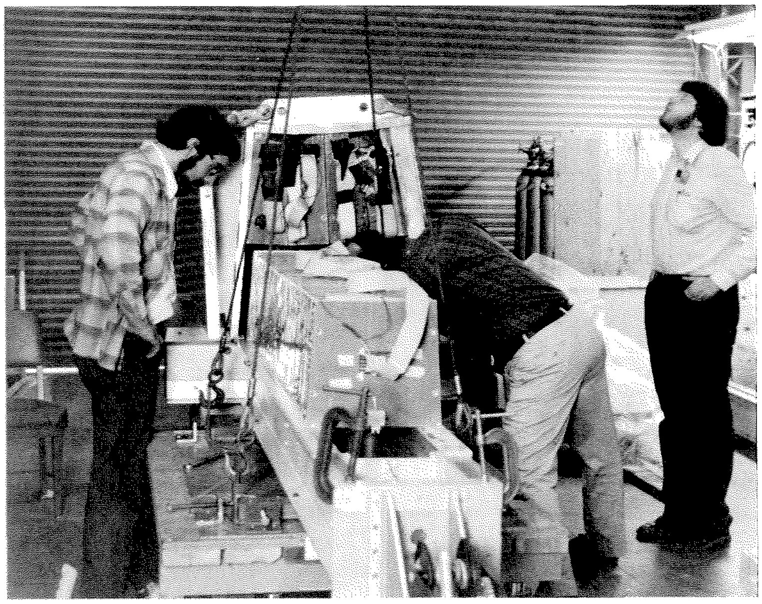
By measuring the total energy of all decay products of the Z^0, the calorimeter "takes the temperature" of each event, hence its name. This method of total energy measurement has several advantages. First, the technique is independent of the detailed structure of any particular event. It does not depend on the number or type of particles into which the Z^0 has decayed. Since events are very complex, the ability of the calorimeter to make this measurement independent of event type is particularly valuable. At high energies many detected events consist of jets — tightly grouped bunches of particles. Reconstructing the parameters of a jet by measuring the individual constituents can be difficult. A calorimetric measurement generally provides the most precise information on jet properties, because it does not require measurement of the parameters of the individual particles in the jet.

The primary function of the calorimeter, however, is the detection of "missing" energy. This somewhat paradoxical goal is the key to many of the more interesting experiments that can be carried out at the Z^0 resonance. Many of the new phenomena sought by high energy physicists as evidence for the validity of GUTs and related theories have a common signature. The new particles produced (in our case through the decay of the Z^0) are predicted to decay further in a characteristic fashion. A significant fraction of *their* decay products are particles such as neutrinos (or even other hypothetical objects such as photinos, gluinos, and Goldstinos), which interact very weakly with matter. The energy carried off by these particles will thus not be registered in the calorimeter. Comparison of the well-known initial-state energy (the mass of the Z^0, that is, the sum of the energies of the incoming electron and positron beams) with the total final-state energy detected by the calorimeter will show a discrepancy. This missing energy is the most powerful signature we have for the production of new particles required by unified theories. The discovery of the W boson at CERN was in fact made possible only by the use of an analogous calorimetric technique, which took advantage of the fact that the W boson decays into an electron or muon accompanied by a neutrino, whose energy is not registered in the detector.

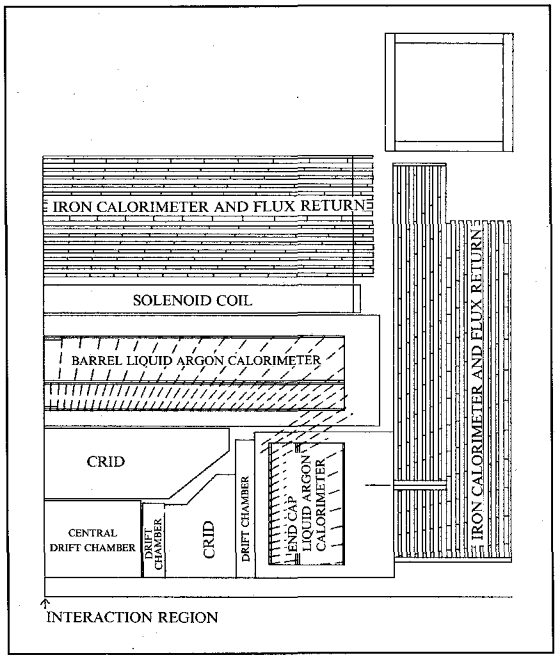
Construction of a calorimeter capable of identifying events with missing energy is no small undertaking. It is vital that the calorimeter be hermetic, that is, that it allow no detectable energy to escape. The calorimeter must therefore completely surround the interaction region and have no substantial leakage paths through the support structure or out the ends. The SLD calorimeter surrounds the interaction region with a large cylindrical annulus, called the barrel, 12 feet in internal diameter, 20 feet long and more than 3 feet thick. The ends of the cylinder are plugged by two end caps, also 3 feet thick. The complex internal structure of the calorimeter consists of more than a million individual elements. It has more than 50 layers of lead absorber and weighs more than a million pounds. Particles produced in Z^0 decay enter the calorimeter, interact with the lead, and produce showers of secondary particles. The energy of these showers is then detected by a sensitive medium consisting of very pure liquid argon at a temperature of 86 K. When the secondary shower particles pass through the liquid argon, they ionize it, producing an electric charge, which is then drifted in an electric field to collecting plates, amplified, and measured. The charge collected is proportional to the detectable energy produced in the Z^0 decay.

We want to measure more than just the temperature of the event; we must also find the direction and shape of the energy flow. The barrel and end caps are divided into segments, forming a projective structure much like the lenses of a fly's eye, which converge to a point. The 35,000 projective segments are formed by tiles of lead that are incorporated into alternate layers of the radiator structure and wired together into towers pointing in toward the interaction region. This allows us to measure both the direction and energy of all the particles in a collision. The complete calorimeter "sees" more than 99 percent of the neutral particles (photons) and about 97 percent of all the other types of particles that emerge from collisions.

Before deciding on the final design, we have had to perform an elaborate series of prototype studies to optimize the calorimeter's performance and to choose between alternative engineering approaches. Such a prototype program has been under way for the last two years. Last spring at Caltech we completed the construction of an eight-ton prototype of one section (about 1 percent of the total), which embodies most of the final design choices for the barrel calorimeter. We successfully tested this prototype in a beam of pions at SLAC in May and we are now working out the final design in detail. Actual construction will begin early in 1986 and will take three years. When completed, the SLD detector promises to yield new insights into the structure of the currently accepted theories of elementary particle physics and to provide one of our best opportunities to see beyond current ideas to the next level in our attempt to unify the forces of nature. □



Dave Hitlin (center) peers into the prototype section of the liquid argon calorimeter for a final inspection before it is tested at SLAC. Rafe Schindler (left) and research fellow Gerald Eigen look on.



The diagram at left shows a vertical section in the plane (including e^+e^- beams) of one quadrant of the detector.