LEP, THE WORLD'S BIGGEST ACCELERATOR, IS ON THE AIR

LEP, by far the largest scientific instrument ever built, has begun doing physics. This 27-km-circumference electron–positron collider ring, bestriding the French–Swiss frontier at CERN, delivered up its first Z^0 particle shortly before midnight on 13 August—a scant 8 minutes after its countercirculating beams of 45.5-GeV positrons and electrons were first brought into collison. Thus the world's second "Z^0 factory" was in business just 30 days after it was handed over by its builders on Bastille Day.

Such are the mercies of "conventional" accelerator technology—albeit on a quite unprecedented scale. LEP, for all its great size and energy, is essentially a conventional e^+e^- storage-ring collider, much like its highly productive lower-energy predecessors. By contrast, the Stanford Linear Collider, the rival Z^0 factory on this side of the ocean, did not yield its first Z^0 until April of this year, an agonizing two years after its last piece was put in place. (See PHYSICS TODAY, July page 17).

The SLC is a single-pass collider rather than the usual storage ring. Its novel design, requiring beams of much smaller cross-section than one needs in a storage ring whose circulating beams collide again and again, confronted the builders of the SLC with a daunting array of problems. But the effort was deemed to be justified because single-pass colliders seem to be the only feasible way of building the next generation of e^+e^- colliders, with beam energies on the order of a TeV (1000 GeV). Because of the synchrotron radiation problem inherent in storing beams of light, charged particles, a TeV electron–positron storage ring would require a tunnel about 130 kilometers around.

The LEP tunnel

LEP requires a 27-km ring to keep energy loss by synchrotron radiation within tolerable limits. The rate at which a charged particle of mass M and energy E circulating in a storage ring of radius R radiates away its energy is proportional to $(E/M)^4/R^2$. Thus the LEP tunnel, designed to hold 100-GeV e^+ and e^- beams in the future, has to be almost 10 times as long as the Tristan e^+e^- storage-ring collider in Japan, designed for 35-GeV beams.

Because the synchrotron radiation scales as M^{-4}, the 1000-GeV Tevatron proton–antiproton storage ring at Fermilab can be much smaller than LEP. Proton rings are limited only by the strength of available bending magnets. The dipole magnets of the LEP ring, by contrast, only need to provide bending fields up to a kilogauss—two orders of magnitude less than the state of the art. But the day may come when much more powerful bending magnets will be installed in the LEP ring: CERN Director General Carlo Rubbia looks forward to the eventual storage of 8-TeV proton beams in the LEP tunnel, which would make this machine something of a competitor of the Superconducting Super Collider planned for Waxahachie, Texas. (See the story on page 51.)

The excavation of the LEP tunnel began in September 1983. The tunnel is below ground at depths of 100 to 150 meters, the storage ring lying in a plane inclined 0.8° to the horizontal so as to minimize its depth in the short segment that runs under the foothills of the Jura mountains north of Geneva. The original 1981 plan had called for 12 km of tunnel under the Jura, as deep as 1000 meters under the surface in some places. "But I thought that was much too risky," recalls Emilio Picasso, director of the LEP construction project. "The greater the depth," he explained, "the greater the pressure of threatening groundwater." At Picasso's insistence, the proposed site was shifted so that now only 3 km of the tunnel lies in the Jura limestone, and the ground cover nowhere exceeds a depth of 150 m.

Picasso's caution proved to be justified. The excavation in the clay "molasse" under the plain that runs from Lake Geneva to the Jura was accomplished quite rapidly and uneventfully by three gigantic tunnel-boring machines. In the tricky Jura limestone, however, more laborious and cautious "blast and drill" excavation was required. In spite of the precautions, two large water leaks during the Jura excavation set the civil engineering schedule back by 20 months. But in the end, the completion of the accelerator, in July 1989, was only 6 months behind the originally envisioned date. The builders had made up much of the time lost in the Jura excavation by accelerating the machine installation schedule in other parts of the tunnel.

The accelerator

Electrons and positrons are injected into the main LEP ring at 20 GeV, having been preaccelerated in a sequence that begins with a 200-MeV electron linac and ends with the Super Proton Synchrotron, a 315×315-GeV proton–antiproton collider that now does part-time duty as the LEP injector.

In the main ring the electrons and positrons traverse a common chain of bending dipole magnets and focusing quadrupole magnets in opposite directions. The two countercirculating stored beams are brought repeatedly into collision in four cavernous underground experimental halls spaced around the ring. Each of these intersection points is surrounded by one of the four large detector complexes that track and identify the products of the e^+e^- collision events. Most of the LEP dipoles and quadrupoles are normal, room-temperature magnets, but special superconducting quadrupoles near the intersection points serve to focus the beams down to 12 microns vertically and 300 microns horizontally at the collision foci. In the four-day mid-August pilot physics run that bagged about 50 Z^0's in the four detectors, the superconducting quadrupoles were not yet turned on. "We wanted to study the beam dynamics in the accelerator in this first run without any added complications," Picasso told us.

And indeed this pilot run disclosed one serious, unanticipated problem in the beam dynamics. Beam oscillations in the horizontal plane, it turned out, were transfering into the vertical plane an order of magnitude more severely than anyone had expected. This undesirable coupling between horizontal and vertical beam modes would make it impossible to squeeze the beam vertically down to the 12-micron design value once the superconducting quadropoles were turned on. The collider's luminosity—its event rate at each collision point per unit scattering cross section—is inversely proportional to the geometric cross section of the beams at the collision foci. So long as the horizontal beam oscillations generated by the injection process continued to excite vertical oscillations to the pathological extent seen in the pilot run, the luminosity of the machine would remain well below its design value of 1.7×10^{31} events per second per cm^2.

At the end of August, the cause of the excessive horizontal–vertical coupling had not been pinned down, but a satisfactory fix-up had apparently been found. The accelerator's 1672 bending magnets are, of course, not perfect dipoles. Their magnetic field configurations have small quadrupole and higher-multipole components. The anomalous horizontal–vertical coupling exhibited by the beam is probably the cumulative effect of a very small skewed quadrupole field component in the ring's 20 kilometers of bending magnets. Because the skewed field component causing the trouble is so minuscule—not much larger than the Earth's magnetic field—it is almost impossible to measure directly.

It was known that the large solenoid magnets of the four LEP particle detectors would contribute some horizontal–vertical beam coupling—but not nearly enough to account for what was found in the pilot run. To cancel the effect of the solenoids on the beam, special quadrupoles, purposely skewed from the horizontal and vertical, had been designed into the beam near the four detectors. On the last day of August the beam experts were finally able to find a current configuration for these corrective skewed quadrupoles that appears to solve the problem—canceling out the horizontal–vertical coupling not only from the detector solenoids but also from the more serious unidentified culprit.

The detectors

Each of the four LEP detectors is itself an enormous enterprise run by an international collaboration of hundreds of particle physicists from dozens of institutions. Each is an elaborate complex of diverse elements, weighing in excess of 3000 tons. The four detectors operate simultaneosly when the accelerator is on, each examining e^+e^- collisions at its own beam-intersection point. Though they have much in common, they are designed to have different, complementary special strengths.

▷ OPAL (Omni-Purpose Apparatus for LEP) is the most conservatively designed of the four detectors, relying principally on well-established detector techniques. Its solenoid magnet is not superconducting. The purpose of the solenoids in all these detectors is to determine the momentum and charge sign of a charged particle emerging an from e^+e^- collision by its curvature in the magnetic field. The central drift chamber that tracks the charged particles in the OPAL magnetic field is surrounded by an array of lead glass blocks that measure photon and electron energies (the "electromagnetic calorimeter") and a layered sandwich of iron plates and streamer tubes that serves as a hadron calorimeter. This iron also serves as the magnet's return yoke and as a filter that allows only muons to pass on to the drift-chamber detectors outside the yoke. OPAL is a collaboration of 22 European, North American and Asian institutions, led by Aldo Michelini of CERN.

▷ ALEPH (Apparatus for LEP Physics) is the simplest of the four detectors, in the sense that it has the fewest components. The emphasis is on reliability. A solid-state microstrip vertex detector surrounding the collision point tracks very short-lived particles. It is surrounded by a large time-projection chamber that tracks charged particles and identifies them by the rate at which they ionize the chamber's gas. This tracking chamber is followed by a fine-grained electromagnetic calorimeter. All these components sit in a superconducting solenoid magnet 6 meters long and 6 meters wide, which produces a 1.5-tesla field. The hadron calorimeter is distributed over the end caps and the magnet's return yoke, beyond which there are the usual muon detectors. The 30-institute ALEPH collaboration of European and US institutions is led by Jack Steinberger of CERN.

▷ DELPHI (Detector with Lepton, Photon and Hadron Identification) incorporates ring-imaging Čerenkov counters to identify charged hadrons by their velocities, their momenta being know from the curvature measured by a large time-projection chamber in the magnetic field of DELPHI's superconducting solenoid. Čerenkov counters of this innovative design have never before been used on a large scale. High-resolution three-dimensional electromagnetic calorimetry is achieved by means of a novel high-density projection chamber that incorporates lead layers in which traversing electrons and photons generate showers into the chamber's ionizing gas medium. Ugo Amaldi (CERN) leads the DELPHI collaboration of 40 institutions from Western and Eastern Europe and the US.

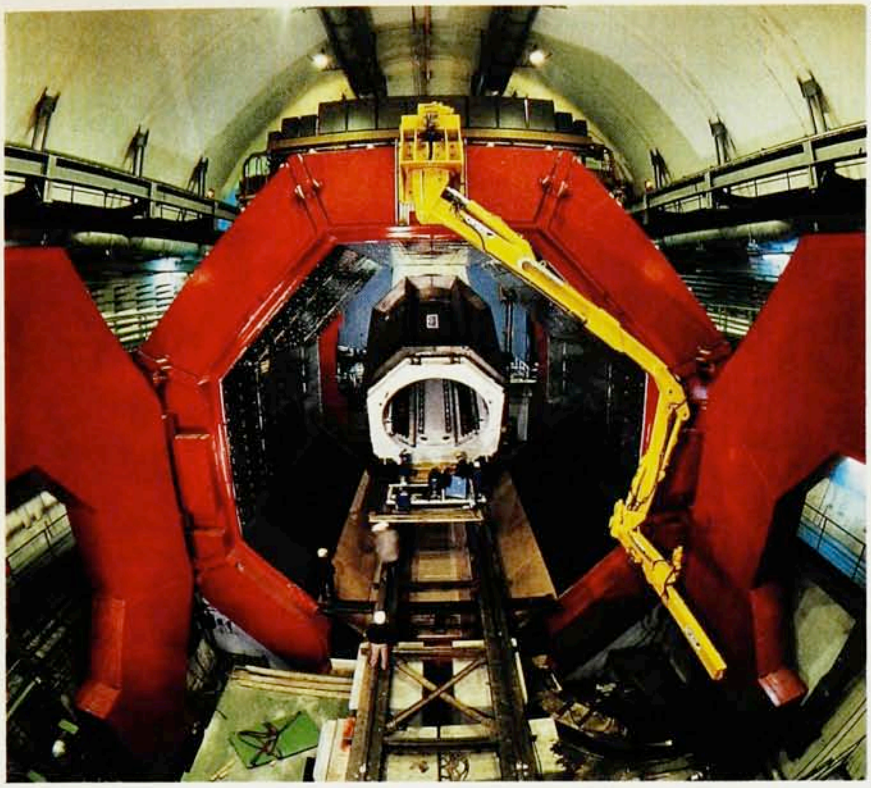
▷ L3 is also known as "Ting's detector," after Samuel C. C. Ting (MIT), the leader of the L3 collaboration of 38 institutions from Beijing to Hawaii (the long way round). With its 13 participating US university groups, L3 involves by far the largest US financial contribution to LEP. The collaboration also includes a large Soviet contingent. The 8000-ton L3 is the biggest of the four detectors. It is specialized "to measure photons, electrons and muons very precisely," as Ting puts it, "and to explore new, unknown phenomena not yet predicted by the theory." The entire detector complex is enclosed within its massive magnet yoke, which just about fills the experimental hall. (See the photograph on page 19.) The L3 solenoid, like OPAL's, is not a superconducting magnet. The electromagnetic calorimeter consists of 10 000 crystals of bismuth germanium oxide, a scintillator material never before used on such a scale. This calorimeter is surrounded by a hadron calorimeter followed by high-precision muon tracking chambers.

The physics program

After the brief pilot physics run in August, the next four weeks were given over to machine development. The first full-fledged physics run was scheduled to begin in mid-September, with the beam energies to be kept near 45.5 GeV, roughly half the mass of the Z^0. The cross section for the formation of Z^0 particles in e^+e^- collisions peaks when the sum of the incident energies precisely equals the central value of the Z^0 mass. Because the Z^0 only lives for about 10^{-25} seconds, its resonant mass peak has an intrinsic width of several GeV.

The Z^0 is presumed to be the intermediate vector boson that mediates those weak interactions in which no electric charge is exchanged—the so-called neutral-current interactions. It has the same quantum numbers as the massless photon, except that it is almost a hundred times heavier than the proton. The existence of the Z^0 was predicted by the theoretical unification of the weak and electromagnetic interactions in the early 1970s and confirmed by Rubbia and his colleagues at the CERN SPS in 1983. The precise values of the Z^0 mass and width are crucial parameters for testing the now "standard model" of the elementary particles. (See PHYSICS TODAY, July, page 17.)

At the LEP design luminosity of 1.7×10^{31} $cm^{-2}\,sec^{-1}$, each detector can expect to see more than 10^4 Z^0's *per day* when the LEP beams are tuned precisely to half the beam mass. The creation of a Z^0 by the union of an electron and a positron is made manifest by its prompt decay into a pair of charged leptons or jets of hadrons.



CERN

Installation of the central support tube of the L3 detector in one of the four underground experimental halls at LEP. The massive 16-meter-high red enclosure is the iron yoke of the L3 detector's solenoid magnet, the largest magnet ever built for high-energy physics. The magnet surrounds the entire detector complex, an unusual configuration designed to provide precise measurements of muon momenta. When this picture was taken last fall, most of the components of the 8000-ton L3 detector were yet to be installed.

During the pilot run, the machine's luminosity was only about 10^{28} $cm^{-2}\,sec^{-1}$, but with the superconducting quadrupoles in action and the horizontal–vertical coupling problem apparently solved, the September run was expected to yield about 10 Z^0's per detector per hour from the start. Luminosity is proportional to the product of the circulating electron and positron currents. The design luminosity assumes that LEP will eventually store 3-mA currents in each beam. The goal for the end of this year is a more modest 1 mA in each beam, providing a luminosity of 10^{30} $cm^{-2}\,sec^{-1}$ by year's end.

Recent Z^0 results

The race to provide the first precision measurement of the Z^0 mass—a race that began at the start of the decade, when Stanford's Burton Richter proposed to build the SLC before the completion of LEP—is already over. In the end it turned out to be a three-horse race. The 14 August issue of *Physical Reviw Letters* contains back-to-back letters by the SLC group[1] and a group of experimenters at Fermilab's Tevatron,[2] reporting measurements of the Z^0 mass close to 91 GeV, with comparable uncertainties on the order of 0.3%.

The ± 0.36 GeV uncertainty given for the Fermilab result came as something of a surprise to those who did not believe a $\bar{p}p$ collider capable of measuring Z^0 parameters with such precision. At an e^+e^- collider one gets the mass of a particular Z^0 simply by summing the energies of the two incident beam particles. At a hadron collider like the Tevatron, by contrast, one must measure the four-momenta of all the Z^0 decay products. It turns out, however, that the admirable qualities of the CDF detector at the Tevatron, together with a clever sequence of interlocking calibrations devised by the CDF experimenters, has yielded a mass measurement of impressive precision. But in the long run, the hadron-collider measurements are limited by systematic uncertainties.

At the Europhysics conference last month in Madrid, the Stanford group, having harvested 332 Z^0's, reported an updated mass determination of 91.17 ± 0.17 GeV. More striking was their reported preliminary measurement of the number of "generations" of elementary particle in nature. Each generation is supposed to have its own brand of neutrinos, and thus each contributes an invisible $\nu\bar{\nu}$ mode to the Z^0 decay. We already know of three such generations, associated respectively with the electron, the muon and the tau lepton—each with its own quarks and neutrinos. From the height and width of the observed Z^0 resonant mass peak, the Stanford group reported a measurement of 2.7 ± 0.7 generations, which corresponds to an upper limit of of 3.9 generations at the 95% confidence limit. As LEP and the SLC begin to accumulate much higher statistics, we should have a definitive result before year's end.

Early in the next decade CERN plans to increase the LEP energy above 81 GeV per beam, the threshold for producing pairs of W bosons, the charged cousins of the neutral Z^0. The Feynman diagram for the production process

$$e^+ + e^- \rightarrow W^+ + W^-$$

involves a virtual Z^0 in the "three-gauge-boson vertex" $Z \rightarrow WW$. Such vertices represent a crucial untested sector of the standard model, which has thus far come through every other experimental trial unscathed.

With LEP's present complement of 128 copper rf accelerating cavities, its energy cannot exceed 55 GeV per beam. (See the cover of this issue.) Over the next several years the copper cavities will gradually be replaced by superconducting niobium rf cavities being developed at CERN. By the end of 1992 the schedule calls for 196 superconducting rf cavities to be in place, yielding beams of 96-GeV electrons and positrons.

—BERTRAM SCHWARZSCHILD

References

1. G. S. Abrams *et al.* (Mark II collaboration), Phys. Rev. Lett. **63**, 724 (1989).
2. F. Abe *et al.* (CDF collaboration), Phys. Rev. Lett. **63**, 720 (1989).

DOES QUANTUM MECHANICS HAVE NONLINEAR TERMS?

One hears about testing quantum electrodynamics or relativity theory, but the theoretical basis of quantum mechanics is rarely questioned. Nevertheless, Steven Weinberg (University of Texas) has recently called for high-precision tests of quantum mechanics that are independent of any particular quantum mechanical theory.[1] To pave the way for an examination of quantum mechanics, he has suggested one possible way of generalizing quantum mechanics to make it nonlinear. As Eugene Wigner pointed out in a 1939 paper, the linearity of quantum mechanics is an important assumption and one that may not necessarily always prove true. Weinberg stressed to us that he does not really feel that quantum mechanics is in any immediate danger, but he does believe that we can learn by questioning it: If we find that quantum mechanics cannot be generalized any further, we may come to understand better why it works so well. If we find that the theory can be generalized in a plausible way, then we must ask why ordinary quantum mechanics is so nearly valid—and we may discover some hidden physics in the process.

Weinberg has suggested one particular example in which a nonlinearity might manifest itself, and several experimental groups have taken up the search for it. The first results are now in: John Bollinger, Daniel Heinzen, Wayne Itano, Sarah Gilbert and David Wineland of the National Institute of Standards and Technology (Boulder, Colorado) have set a very low upper limit on the size of a possible nonlinear term in the hyperfine splitting of a beryllium atom. Bollinger presented these results at the annual meeting of the APS division of atomic, molecular and optical physics, held in Windsor, Ontario, last May.[2]

Quantum mechanics has been tested in several ways before. One set of experiments aimed to distinguish it from local hidden-variable theories. (See the article by David Mermin in PHYSICS TODAY, April 1985, page 38.) These experiments succeeded in ruling out hidden variables, but Weinberg points out that they did not test quantum mechanics to better than about one percent. Another approach to testing quantum mechanics dealt with the incorporation of nonlinear terms into the Schrödinger equation. In 1980, at the suggestion of Abner Shimony[3] (Boston University), a team led by Clifford Shull[4] (MIT) used neutron interferometry to search for possible nonlinear terms of a form suggested by Iwo Bialynicki-Birula and Jan Mycielski[5] (University of Warsaw). Roland Gahler (Technical University of Munich), Anthony G. Klein (University of Melbourne, Australia) and Anton Zeilinger[6] (Technical University of Vienna), working at the Laue–Langevin Institute in Grenoble, followed with a similar experiment that set more stringent limits on the size of the nonlinear term.

Nonlinear formulation

Weinberg set out to make the most general formulation possible that is still consistent with essential properties of quantum mechanics. A key requirement was to preserve homogeneity—to ensure that if one wavefunction is a solution of the Schrödinger equation, then so is another wavefunction that is just a constant multiple of the first. The nonlinear term introduced by the Polish theorists did not satisfy this condition. Weinberg assumes that the time dependence of the wavefunction is given by:

$$i\hbar\frac{d\Psi_k}{dt} = \frac{\partial h(\Psi,\Psi^*)}{\partial \Psi_k{}^*}$$

This equation reduces to the standard form if the Hamiltonian function h has the bilinear form $\Psi_k{}^* H_{kl}\ \Psi_l$, but allows for treatment of possible terms in the Hamiltonian that are not bilinear. In the example of a generalized two-component system, Weinberg shows that the Hamiltonian function h can be put in the form $n\ \bar{h}(a)$, where n is the norm $|\Psi_1|^2 + |\Psi_2|^2$ and $\bar{h}$ is an arbitrary function of the variable $a = |\Psi_2|^2/n$.

For an atom undergoing a radiative transition (such as that between two hyperfine levels), Weinberg's equation predicts that the resonant transition frequency will be sensitive to the occupancy of the two levels. This transition frequency will change as these occupancies change. If one drives a certain transition with an applied monochromatic oscillator, detuning will result because the resonant transition frequency will shift as the oscillator continues to populate the upper levels. For a weak nonlinearity, the shift in frequency will be small. To detect it, one must make the coupling between the oscillator and the atom as weak as possible so that the transition takes a long time. The sensitivity of the technique thus varies inversely with the time of perturbation.

Weinberg used data from a 1985 experiment performed at NIST[7] (then called the National Bureau of Standards) to estimate an upper limit on the size of the nonlinear term. In that experiment, Be^9 ions were driven from one state to the other with a single pulse about 1 second long. Because the transition could be driven with such a pulse, Weinberg inferred that the nonlinearity could not lead to a shift of more than the inverse of that pulse length, or 1 Hz, which corresponds to a nonlinear term on the order of 10^{-15} eV.

Norman Ramsey (Harvard University) in 1949 originated a technique for measuring atomic resonant transitions and hence for setting frequency standards. This so-called method of separated oscillatory fields gives a sensitive way to detect changes in transition frequencies. First, an rf pulse is applied to an atom and then turned off. This creates a superposition state, with specific populations of the two atomic levels, that depends on the amplitude, frequency and length of the pulse. After a certain time interval, a second rf pulse of the same length, coherent with the first, is applied. If the two rf pulses are at the resonant transition frequency, the second pulse will be in phase with the superposition state and it will continue to transfer the ions to the upper state. The rf frequency is changed until this resonant condition is met.

If a nonlinearity is present, the phase of the superposition state will not be determined simply by the difference between the energy eigenvalues of the two levels but will also depend on the state amplitudes creat-