The Z Boson

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The discovery of the Z boson 7 years ago verified a key prediction of the unified theory of electromagnetic and weak forces. Today an experimental program is beginning at two electron-positron colliders to study the properties of the Z particle in great detail. The data accumulated will subject the unified theory to more rigorous tests and will probe with great sensitivity for new physics not encompassed by the existing standard model of the elementary particles and forces. Questions under study include the number of quark and lepton families, the mass of the still undiscovered top quark, and the search for the still unknown fifth force of nature required by the theory to generate the masses of the elementary particles.

THE Z BOSON IS ONE OF THE FUNDAMENTAL QUANTA THAT transmit the four known forces of nature. Just as the photon, gluon, and (still unobserved) graviton mediate the electromagnetic, strong, and gravitational interactions, the Z and its sibling W boson are the mediators of the weak interaction. As recently as 1983 the Z was only a theoretical hypothesis. Today two Z "factories" have begun operation with the goal of studying the decays of millions of Z particles. This rapid transformation from hypothesis to research tool is especially dramatic because the particular force mediated by the Z boson, the "neutral current" weak interaction, was itself unknown until 1973.

The Z was discovered in 1983 at the CERN proton-antiproton collider in Geneva, Switzerland, operating at an energy of 270 GeV per beam (*1*). (One gigaelectron volt is 10^9 electron volts and the mass of a proton is 0.938 GeV; I will use the particle physics convention for the speed of light and Planck's constant, $c = h/2\pi = 1$.) The Z mass was first measured at 95 ± 2.5 GeV, in agreement with the prediction of the unified theory of weak and electromagnetic interactions. In the unified theory the electromagnetic gauge symmetry of Maxwell is generalized to a larger gauge symmetry requiring the photon, W, and Z particles as the associated spin 1 gauge bosons (*2*), distinguished from one another by a mechanism (spontaneous symmetry breaking, discussed below) that makes the W and Z massive while leaving the photon massless (*3*). Weak and electromagnetic interactions are then aspects of a single phenomenon, the electroweak force. Since the W and Z weigh about 80 and 90 GeV respectively, the range of the weak force is $\sim 1/M_W \sim 2 \times 10^{-16}$ cm, decidedly subnuclear, which is why the weak force is dramatically different than the electromagnetic force at macroscopic, atomic, and nuclear scales. On the other hand, at energies much greater than the W and Z masses, where one can probe distances much smaller than 2×10^{-16} cm, the intrinsic symmetry of W, Z, and photon interactions should become apparent. The electroweak theory is incomplete in a particularly exciting way: it predicts the existence of a still undiscovered fifth force of nature which generates the masses of the particles that make up our world.

Study of the Z has continued at CERN and at the higher energy Tevatron proton-antiproton collider at Fermilab outside Chicago, operating at 900 GeV per beam. Of order 200 Z decays have now been detected at each laboratory. In 1989 two electron-positron colliders designed to produce Z particles began operation. In addition to larger Z production rates, the electron colliders enjoy one other important advantage: more than 99% of the electron-positron annihilations result in a detectable Z particle when the collision energy is tuned to the Z mass, whereas at proton-antiproton colliders the fraction of events with a detectable Z is orders of magnitude smaller than 1%, with the precise value depending on how the detectors are set to trigger. Proton accelerators have traditionally led in the exploration of new energy domains; more detailed studies are often possible at electron accelerators.

The SLC (Stanford Linear Collider) at Stanford University was the first of these two electron facilities to be completed, with its first Z observed in April 1989. Grafted on to the 20-year-old linear accelerator, at considerably less than the cost of an entirely new facility, the SLC is intended to study the physics of Z boson decays and simultaneously to explore the new technology of linear colliders. Above about 100 GeV per beam, electron-positron storage rings become impractical because of excessive power loss from synchrotron radiation, and linear colliders will be needed, with submicrometer diameter beams required for operation at teraelectron volt energies (*4*). The SLC is a clear success as a technology research and development project and important scientific results have been obtained from the 500 Z particles detected in its first months of operation. Technical improvements now in progress will determine whether it will eventually produce enough Z particles to earn the designation of a Z "factory." The ability to study Z decays with a longitudinally polarized electron beam will allow the SLC to compensate for lower luminosity in fundamental precision tests of the electroweak theory.

The second facility is LEP (Large Electron Positron storage ring) at CERN. Considerably more costly than the SLC, LEP is based on conventional storage ring technology and occupies a 27-km circumference tunnel, the world's largest scientific instrument. The first Z particles were observed at LEP in September 1989. As of this writing the four LEP experiments have detected a total of about 100,000 Z decays. With these data they rapidly confirmed the results obtained at the SLC and have gone on to further studies requiring higher statistics. LEP seems well on the road to its design goal of 3 million Z particles per year.

The Physics Framework

Nuclear beta decay was the first known manifestation of the weak interaction: a nucleus of electric charge Z emits an electron and becomes a nucleus of charge $Z + 1$. Because the interaction changes

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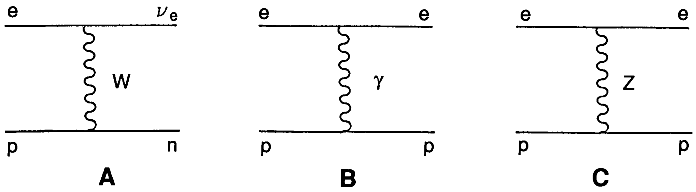

Fig. 1. Feynman diagrams for electron proton scattering by (**A**) charged-current weak interaction, (**B**) electromagnetic interaction, and (**C**) neutral-current weak interaction.

the nuclear charge, it is called the "charged-current" weak interaction. The apparent violation of energy and angular momentum conservation in beta decay led Pauli to postulate the existence of the neutrino, presumed to be emitted with the electron and to escape detection by virtue of its very weak interaction with ordinary matter (*5*). Pauli was of course right; today neutrino beams are a common tool of high energy physics experiments.

Fermi described Pauli's idea by an effective four-particle interaction of the proton, neutron, electron, and neutrino. Yukawa later hypothesized that Fermi's interaction is mediated by exchange of a massive particle (*6*), now called the W boson, just as photon exchange mediates the electromagnetic force. This is illustrated in Fig. 1, A and B, where the Feynman diagrams for electron-proton scattering by weak charged-current and electromagnetic interaction are shown.

The strongest motivation for considering the possibility that the weak force might also exist in another form came from the elegant attempt to unify the weak and electromagnetic interactions. Drawing on mathematical symmetries of a kind used previously to describe the strong nuclear force, Glashow proposed a model (*2*) based on the symmetry group $SU(2) \times U(1)$ in which the photon and W boson are augmented by an additional massive neutral particle, the Z boson. Z particle exchange (Fig. 1C) then induces a new force: the neutral-current weak interaction.

Glashow's model left the W and Z boson masses as independent free parameters. The model was conceptually incomplete in a crucial respect: it posited that the photon, W, and Z were all gauge bosons, following the generalization of Maxwellian gauge invariance to noncommuting group symmetries by Yang and Mills (*7*), but did not reconcile the contradiction with gauge symmetry posed by the W and Z masses. It was then "nonrenormalizable," meaning that, unlike quantum electrodynamics, higher orders in perturbation theory could not be computed without introducing additional parameters.

This problem was addressed 5 years later in papers by Salam and Weinberg (*3*), applying ideas developed a little earlier by Higgs and others (*8*). These authors had shown that gauge bosons can acquire mass in relativistic field theories without violating gauge invariance if the symmetry is broken not explicitly by asymmetric interactions but "spontaneously" by the ground state of the theory, much as rotational symmetry is broken in a ferromagnet. In its simplest form this idea is implemented by postulating a spin 0 particle, the Higgs boson. Large numbers of Higgs boson quanta condense in the ground state to form a classical field that generates the W and Z masses. Weinberg and Salam wrote down the simplest Higgs boson model needed to complete Glashow's model of the gauge particle interactions. It implied a definite prediction for both the W and Z boson masses in terms of a single parameter, the weak interaction mixing angle θ_W, which could be measured if the neutral current weak force could be observed.

It was, however, very difficult experimentally to verify the existence of the neutral current force, as may be appreciated from Fig. 1. Unlike the charged-current force which creates a different final state (Fig. 1A), the contribution of the neutral-current force to electron proton scattering (Fig. 1C) produces the same final state as electromagnetic scattering (Fig. 1B). If the interaction energy is low relative to the Z particle mass, the result is an extremely small deviation from the electron-proton interaction caused by photon exchange alone.

Interest in this experimental challenge was increased by 't Hooft's demonstration that the Weinberg-Salam model is indeed renormalizable (*9*). Verification of the existence of neutral currents did not come, however, from the study of electron-proton interactions [that demonstration took another 5 years (*10*)], but rather from the study of neutrino-nucleon scattering, a process that occurs only by virtue of the weak interaction, since the neutrino is electrically neutral.

Figure 2A shows the diagram for inelastic scattering of a muon-neutrino, ν_μ, with a proton by charged current interaction: the neutrino is transformed to a muon and the proton to a multiparticle state of net electric charge two, such as a proton and a positively charged pi meson. Such experiments had already been routine for about 10 years. In a bubble chamber the experimental signature is "nothing" coming in and muon and hadron tracks going out. (Hadrons are strongly interacting particles, such as the proton, neutron, and pi meson, but not the electron or other leptons which do not feel the strong force.) The signature of neutral current scattering, corresponding to Fig. 2B, is even more ghostly since "nothing" comes in and only the recoil hadrons formed from the struck proton are observed going out. Neutron contamination was a dangerous background that could create counterfeit neutral current events.

It therefore required no small measure of careful analysis and courage to be the first to assert that neutral currents exist. The first announcement came from the CERN Gargamelle bubble chamber collaboration, including Lagarrigue, Musset, Perkins, Rousset, and co-workers. The evidence was from neutrino-proton inelastic scattering events (*11*), as in Fig. 2B, and a single unambiguous example of neutrino electron elastic scattering (*12*), $\nu_\mu e \rightarrow \nu_\mu e$.

Subsequent experiments confirmed the existence of neutral current interactions in polarized electron proton scattering (*10*) and in atomic physics (*13*). By comparing the cross sections for charged and neutral current interactions, the neutrino scattering experiments posed a quantitative test for the Glashow-Weinberg-Salam model which the model passed (*5*). The experiments also provided a measurement of the one free parameter in the model, θ_W, in terms of which the W and Z masses could be predicted. Confidence in the agreement of the theory with these and other experiments was so high that Glashow, Salam, and Weinberg shared the Nobel Prize in 1979, before the W and Z were observed. Fortunately for the Nobel committee, the W (*14*) and Z (*1*) were discovered with the predicted masses in 1983 at the CERN collider, for which Rubbia and van der Meer shared the 1984 Nobel Prize.

Discovery of the W and Z confirmed what is today called the "standard model," in which the strong, weak, and electromagnetic forces are all described by gauge theories, and the fundamental building blocks of matter are "families" of spin 1/2 quarks and

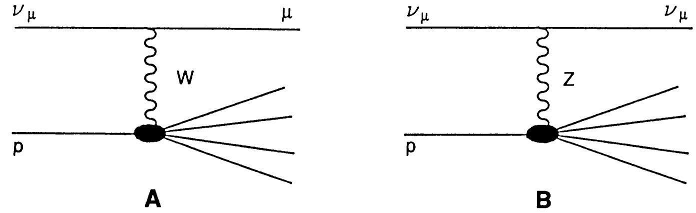

Fig. 2. Inelastic scattering of a muon-neutrino from a proton target by (**A**) charged-current and (**B**) neutral-current weak interactions.

Table 1. Quarks and leptons of the standard model. Masses are indicated in parenthesis in each entry. Since quarks are confined to hadronic bound states, their masses are only measured indirectly.

	Quarks		Leptons	
Electric charge:	Q = 2/3	Q = −1/3	Q = −1	Q = 0
Family 1	u (~4 MeV)	d (~8 MeV)	e (~0.51 MeV)	ν_e (<18 eV)
Family 2	c (~1.5 GeV)	s (~150 MeV)	μ (~106 MeV)	ν_μ (<0.25 MeV)
Family 3	t (>78 GeV)	b (~5 GeV)	τ (~1.78 MeV)	ν_τ (<35 MeV)

leptons. The first family contains the up and down quarks (which are the constituents of the proton and neutron), the electron, and the electron-neutrino. The second family contains the charm and strange quarks and the muon and muon-neutrino, while the third family contains the (still undiscovered) top quark, the bottom quark, and the tau lepton and its associated neutrino. The electric charges and masses of the quarks and leptons are displayed in Table 1.

Though elegant and compact compared to the starting point of elementary particle physics in the 1950s, the standard model is clearly incomplete. For instance, we do not understand the precise genesis of the W and Z masses, the family structure and mass spectrum of the quarks and leptons, and whether there are additional gauge interactions, perhaps embodying deeper unification beyond the electroweak unification already achieved. These are all profound questions, for which the answers may not come easily. In particular, within the general framework of spontaneous symmetry breaking, the mechanism of W and Z mass generation must involve a new force of nature, perhaps mediated by the Higgs boson or perhaps by some other set of new particles (*15*).

First Results

Neutrino counting. Data obtained in the first months of SLC and LEP operation has already answered one of the fundamental open questions in the standard model. From the Z resonance excitation spectrum (Fig. 3) we can already conclude that there are just three quark-lepton families, within the framework of the original Glashow-Weinberg-Salam model, in which the neutrinos are massless. This is a powerful result since within this framework it rules out arbitrarily heavy quarks and charged leptons, which could not have been searched for directly without increasingly energetic accelerators.

The conclusion is possible because in the standard model the Z would decay to any additional neutrinos with a known rate, causing its width to broaden. Including just the quarks and leptons shown in Table 1 (except the top quark which is too heavy), the Z width is predicted to be 2.484 GeV, of which each neutrino contributes 0.166 GeV. The Z width (in gigaelectron volts) for N_ν neutrinos is then

$$\Gamma_Z = [2.484 + (N_\nu - 3)0.166] \qquad (1)$$

Measurements of Γ_Z then constrain N_ν. For instance, a recent measurement by the L3 collaboration based on 12,500 Z decays to hadronic final states gives $\Gamma = 2.539 \pm 0.054$ GeV corresponding to $N_\nu = 3.32 \pm 0.32$ (*16*). Similar results have been reported by the ALEPH (*17*) and OPAL (*18*) collaborations, as well as a consistent result from the Mark II collaboration at the SLC based on fewer events (*19*).

A more precise determination of Γ_Z is obtained from the Z production cross section, since the cross section is inversely proportional to the square of the Z width:

$$\sigma(e^+e^- \rightarrow Z \rightarrow \bar{f}f) = \frac{12\pi\Gamma(Z \rightarrow e^+e^-)\Gamma(Z \rightarrow \bar{f}f)}{M_Z^2\Gamma_Z^2} \qquad (2)$$

Using the standard model predictions for the decay widths to the known quarks and leptons, one can see that a measurement of the cross section implies a value for Γ_Z and therefore for N_ν. With this method the ALEPH collaboration has used 18,500 Z decays to obtain $N_\nu = 3.01 \pm 0.15 \pm 0.05$, excluding a fourth massless neutrino by 6 standard deviations (*17*). (When two uncertainties are quoted, the first is statistical and the second is systematic.) Comparable results have been announced by the OPAL (*18*) and L3 (*16*) experiments, as well as a consistent result from the Mark II collaboration (*19*).

It is, however, straightforward to modify the theory so that neutrinos are massive. If fourth and higher generation neutrinos were heavier than $M_Z/2$, they would, of course, not be pair-produced in Z decays. With this caveat additional quark-lepton families remain a possibility.

Higgs boson search. The "Higgs mechanism" is the only known means of generating mass for the W and Z gauge bosons without violating gauge invariance. The essential features are a new sector of particles and a new force, such that the state of lowest energy contains a classical field that "spontaneously" selects a preferred direction in the symmetry space of the gauge invariance. In the simplest implementation of this idea, that of the papers of Weinberg and Salam (*3*), there is just one new particle, the Higgs boson, which forms the symmetry breaking field. However the "Higgs mechanism" can occur in other ways, with multiple Higgs bosons or with none at all.

While the Weinberg-Salam construction appears at first glance to be simple and elegant, it requires unnatural "fine-tuning" of the parameters, a sign that nature may have made a different choice (*15*). There are two known approaches within the Higgs mechanism framework that address this fine-tuning problem. The first, supersymmetry (*20*), requires the existence of more than one Higgs

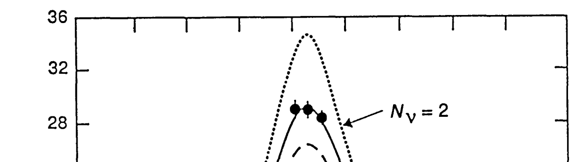

Fig. 3. Z resonance excitation spectrum as measured by the *L3* collaboration (*16*). The dotted and dashed lines are the standard model predictions for two and four neutrino species, respectively. The solid line is a fit to the data with the number of neutrinos left as a (not necessarily integral) free parameter.

boson. The second, "technicolor" (*21*), is patterned after the theory of the strong nuclear force, quantum chromodynamics. In technicolor models the symmetry breaking condensate results from strong interaction dynamics and there are no Higgs bosons at all, but rather a rich spectrum of particles around 2 TeV = 2000 GeV interacting by a new strong gauge interaction. In any case, it follows from unitarity (probability conservation applied to the scattering matrix) and gauge invariance that whatever its specific nature, the new physics which breaks the symmetry of the ground state must emerge at a scale not greater than about 2 TeV (*22*).

Because the symmetry breaking sector has by its nature very small interactions with ordinary matter, it is difficult to search for it experimentally. With a sample of a few million Z decays it will be possible to search for the Higgs boson of Weinberg and Salam up to a mass of about 50 GeV and to perform similar searches for the lightest Higgs boson in supersymmetric models. The method is based on Z decays in which the Higgs boson is produced recoiling against a pair of electrons, muons, or neutrinos (*23*). Since the Higgs boson couples to quarks and leptons in proportion to their mass, it will decay primarily to the heaviest accessible quark or lepton pair. The fraction of Z decays of this type is 2.4×10^{-4} for a Weinberg-Salam Higgs boson of 20 GeV, falling to 1×10^{-5} for a 50-GeV Higgs boson.

Using 11,500 Z decays, the ALEPH collaboration has already excluded a Weinberg-Salam Higgs boson lighter than 15 GeV on the basis of a 95% confidence interval (*24*), and has presented a preliminary report based on 24,000 events that raises the 95% confidence level lower limit to 24 GeV (*25*). The OPAL collaboration has obtained a similar 95% confidence level lower limit of 19 GeV (*26*). In addition, the ALEPH collaboration used similar methods to exclude regions of the more complicated Higgs boson parameter space in supersymmetric models (*27*). Though the results may seem modest relative to the 2-TeV expanse in which the physics of symmetry breaking could occur, they are a gratifying advance in the experimental search for this important and elusive physical system that is responsible for the genesis of particle masses.

New particle searches. Many new particles would be copiously pair-produced in Z decays if their masses are less than half the Z mass. Like the example of a fourth generation neutrino discussed above, typical branching ratios are of order a few percent. In the standard model additional heavy quarks and charged leptons have well-specified couplings to the Z, so that their production rates are easily predicted. Using a sample of about 400 Z decays, the Mark II collaboration has established 95% confidence lower limits on the mass of the top quark ($m_t > 40.7$ GeV), a fourth generation quark of charge $-1/3$ ($m_{b'} > 42.0$ GeV), and an unstable heavy Dirac neutrino ($m_{L^0} > 41.3$ GeV) (*28*). Each of these bounds is very near the kinematic limit, $M_Z/2 \simeq 45$ GeV. Similar results are reported by the LEP experiments (*29*). The ALEPH and OPAL collaborations at LEP have also excluded by direct search a fourth generation charge -1 heavy lepton for masses up to nearly the kinematic limit, provided it decays predominantly to a stable and not too heavy fourth generation neutrino (*30*).

The "superparticles" predicted in supersymmetric theories would also be copiously produced as particle-antiparticle pairs in Z decays if they are light enough. Supersymmetry is a beautiful generalization of the concept of symmetry that relates particles of different spin and different (Bose or Fermi) statistics (*20*). It could underlie unification of gravity with the other forces, not possible within the usual gauge theory context, since the graviton has spin 2 while the other gauge particles have spin 1. Supersymmetry might also solve one aspect of the fine-tuning problem of Higgs boson theories mentioned above; if so, superparticles should exist at an energy not much greater than the electroweak scale, probably not larger than 1 or 2 TeV (*15*).

In supersymmetric theories, the spin 1/2 quarks and leptons have spin 0 squark and slepton superpartners, while the photon, W, and Z have spin 1/2 partners, respectively the photino, wino (pronounced weeno), and zino. The interactions of these particles with the Z are determined by supersymmetry and gauge invariance, but their masses are not predicted. The LEP L3 collaboration has searched for superparticles, finding for a 95% confidence interval that the scalar electron and muon cannot be lighter than 41 GeV and the wino not lighter than 44 GeV (the results assume that the photino is lighter than 20 GeV) (*31*). Similar results are reported by the ALEPH (*32*) and OPAL (*33*) collaborations.

Precision tests of the standard model. Just as for quantum electrodynamics, the success of the electroweak theory raises a challenge for more precise tests, both to confirm our understanding and to search for small deviations which could be the first sign of new phenomena beyond the standard model. Very precise measurements are needed of the Z mass and width and of its couplings to leptons and quarks. Such measurements are sensitive to physics at mass scales above those that can be probed directly. For instance, heavy particles can induce significant quantum corrections to the relationships predicted in leading order, and a very heavy Z′ boson, required in some "grand unified theories" unifying strong and electroweak interactions, would mix quantum mechanically with the Z boson of the $SU(2) \times U(1)$ theory, resulting in discrepancies with many standard model predictions.

Though this program is only just beginning, it has already placed an important constraint on the mass of the still undiscovered top quark, which absolutely must exist to maintain the gauge invariance of the standard model. In leading order the W and Z masses are related by a fundamental equation of the theory,

$$M_W = M_Z \cos\theta_W \tag{3}$$

where θ_W is the weak interaction mixing angle which also determines in leading order the couplings of the Z to the leptons and quarks. For instance, the vector and axial-vector couplings of the Z to the charged leptons, $l = e,\mu,\tau$ are equal in leading order to

$$a_l = \frac{-e}{\sin\theta_W \cos\theta_W}$$
$$v_l = \frac{-e(1 - 4\sin^2\theta_W)}{\sin\theta_W \cos\theta_W} \tag{4}$$

where e is the magnitude of the electron electric charge, given in terms of the fine structure constant measured in low energy experiments by $e^2/4\pi = 1/137.035895(61)$. If the top quark is heavier than the W, as it almost surely is [the CDF collaboration at Fermilab reports a lower limit $m_t > 77$ GeV (*34*)], then Eq. 3 is modified by a quantum correction that grows like the square of the top quark mass (*35*),

$$M_W = M_Z \cos\theta_W\left(1 + \frac{3G_F m_t^2}{16\sqrt{2}\pi^2}\right) \tag{5}$$

where $G_F = 1.166344(11) \times 10^{-5}$ GeV is the Fermi constant determined from the muon lifetime. In writing Eq. 5 I take Eq. 4 to define θ_W. Expressed in a somewhat different convention related to the precisely measured muon lifetime (*36*), Eq. 5 and present data imply that the top quark cannot be much heavier than 200 to 250 GeV (*37*).

The Z mass is by far the best measured of the quantities in Eq. 3. For instance, the L3 collaboration recently reported a mass value (*16*) of 91.160 ± 0.024 ± 0.030 GeV. The W mass is less well determined. Using the Z mass values from LEP and SLC for calibration, the UA2 collaboration at CERN found (38) $M_W = 80.49 \pm 0.43 \pm 0.24$ GeV, which implies from Eq. 3 that $\sin^2\theta_W = 0.220 \pm 0.10$. Referring only to their own measurements of the W and Z masses, the CDF collaboration at Fermilab has recently reported (39) the preliminary values $M_W = 79.83 \pm 0.44$ GeV and $\sin^2\theta_W = 0.230 \pm 0.009$.

The weak angle θ_W can also be determined from the partial width for the Z to decay to a lepton-antilepton pair, given in leading order by

$$\Gamma(Z \rightarrow l^+l^-) = \frac{M_Z(a_l^2 + v_l^2)}{192\pi} \quad (6)$$

where v_l and a_l are given in Eq. 4. The ALEPH collaboration reports 83.9 ± 2.2 MeV for the average of the electron, muon, and tau lepton partial widths, implying (17) $\sin^2\theta_W = 0.231 \pm 0.008$, consistent with the values based on the W and Z mass measurements and with previous neutrino scattering, polarized electron scattering, and atomic parity violation experiment measurements (37). It should be stressed that the various measurements of θ_W have different sensitivities to quantum effects, such as those induced by the top quark, since they are based on different definitions of θ_W. In this sense the quoted uncertainties of different measurements may not be directly comparable.

Future Prospects

The study of the Z boson and the electroweak theory is just emerging from its infancy. Significant advances are expected in the coming decade from the projected high energy physics program at European and U.S. laboratories. I will briefly describe the highlights of what can be expected.

High statistics Z decay studies. Within the next few years LEP experiments expect to collect millions of Z decays. This will allow them to extend the precision tests of the electroweak theory. For instance, the dependence of the Z-lepton couplings on the weak mixing angle θ_W (Eq. 4) can be determined with great accuracy from a high statistics (that is, a large number of events) measurement of the forward-backward asymmetry for muon production,

$$A_{FB}(\mu) = \frac{\sigma_F(\mu) - \sigma_B(\mu)}{\sigma_F(\mu) + \sigma_B(\mu)} \quad (7)$$

where σ_F and σ_B are the cross sections for the μ^- to be produced in the forward and backward hemispheres, with forward defined as the direction of the electron beam. The leading order prediction is

$$A_{FB}(\mu) = \frac{3a_l^2v_l^2}{(a_l^2 + v_l^2)^2} \quad (8)$$

where $a_l = a_e = a_\mu$ and $v_l = v_e = v_\mu$ are given in Eq. 4.

Because $\sin^2\theta_W \simeq 0.23$ is near the value 0.25 where v_l would vanish, the asymmetry is suppressed and a very large number of events is required. With 3 million Z's detected in all decay channels, it will be possible to determine $\sin^2\theta_W$ from $A_{FB}(\mu)$ to an accuracy of $\simeq \pm 0.0015$ or about half a percent, an order of magnitude improvement on the existing precision. Because it is only suppressed by one power of v_l, the b quark asymmetry $A_{FB}(b)$ could provide as much as a factor 2 more precision for $\sin^2\theta_W$; measurement of $A_{FB}(b)$ will require recognizing $Z \rightarrow \bar{b}b$ decays in which the b or $\bar{b}$ decays semileptonically to an electron or muon (40). By comparing measurements of θ_W based on the mass ratio M_W/M_Z and the asymmetries A_{FB}, we probe higher order quantum corrections (for example, Eq. 5) imposing constraints on physics not yet observed, such as the top quark and the Higgs boson.

In addition to performing high precision measurements, LEP experiments will be able to use the millions of detected Z's to search for new particles with small production rates. For instance, it will be possible to search for the Weinberg-Salam Higgs boson up to a mass of about 50 GeV. Very large event samples also afford the greatest opportunity for completely unexpected discoveries that could be more important than the phenomena we are planning to seek.

Polarized electron beams. The study of Z bosons produced with longitudinally polarized electrons confers a great advantage in precision studies of the electroweak theory. Linear e^+e^- colliders have significant advantages over circular storage rings in this respect. While transverse polarization arises naturally at storage rings, the polarization time is long and there are strong depolarizing effects. Though an effort may be made at LEP, it is by no means clear that useful physics studies with a longitudinally polarized beam will be feasible (41).

At the SLC an experiment with a longitudinally polarized electron beam is expected to begin this year to measure the left-right polarization asymmetry,

$$A_{LR} = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} \quad (9)$$

where $\sigma_{L,R}$ are the Z production cross sections for left and right polarized electrons, respectively. The standard model prediction for A_{LR} is

$$A_{LR} = \frac{2a_e v_e}{a_e^2 + v_e^2} \quad (10)$$

with $a_e = a_l$ and $v_e = v_l$ given in Eq. 4.

The polarization asymmetry has two obvious advantages over the front-back muon asymmetry: it is only suppressed by one power of v_l and all Z decays contribute to it. The proposal for the SLC experiment calls for beam polarization $P = 45\%$ with uncertainty $\Delta P/P = 0.05$ (42). If that goal is eventually met, then for $\sin^2\theta_W = 0.23$, a sample of 100,000 Z decays would provide a measurement of $\sin^2\theta_W$ to $\sim \pm 0.0013$, slightly better than the precision from the forward-backward muon asymmetry with 3 million Z's. With a polarization of 35% the uncertainty in $\sin^2\theta_W$ would be $\sim \pm 0.0017$. The advantage of the polarization asymmetry over the front-back asymmetry (Eq. 7) increases dramatically as $\sin^2\theta_W$ approaches 1/4, not only because it is linear rather than quadratic in the small quantity v_l (Eq 4) but also because the effect of the uncertainty in the polarization, $\Delta P/P$, is diminished.

LEP II and Tevatron upgrade. With the installation of superconducting radio-frequency cavities, LEP 1 will be transformed in about 1995 to LEP II, with a maximum center of mass energy of 190 GeV and a design luminosity of 2.8×10^{31} cm^{-2} s^{-1}. This will enable a rich experimental program, although with much lower event rates than are enjoyed at the peak of the Z resonance. The added radio-frequency power will also make it possible to operate with increased luminosity at the Z peak (43).

With higher energy it will be possible to extend the search for new phenomena to larger mass scales. In particular, the search for the Higgs boson of the standard model can be extended to about 80 GeV.

One important contribution of LEP II is sure to be the study of W boson pair production, $e^+e^- \rightarrow W^+W^-$, for which the threshold energy is $2M_W = 160$ GeV. At the peak energy and design luminosity, the W pair yield would be 6000 per experimental year ($\sim 10^7$

seconds actual running time), most of which should be cleanly detectable over backgrounds. It will be possible to measure the W mass by a variety of methods (*44*) to an accuracy of about ± 100 MeV, a fourfold improvement on present measurements from proton-antiproton colliders. This will improve the knowledge of $\sin^2\theta_W$ determined from Eq. 3 to an accuracy nearly equal to that expected from determinations based on the asymmetries, A_{LR} and A_{FB}, and Eq. 4. Discrepancies between determinations of θ_W from Eqs. 3 and 4 will arise from quantum corrections (such as Eq. 5) and are a probe of unknown physics, such as the top quark and the Higgs boson or whatever may replace it as the agent of W and Z mass generation.

The W^+W^- differential cross section measurement will provide the first direct probe of the Z-W-W and photon-W-W interactions, for which the theory makes a crucial prediction. The form of the interaction, and therefore the angular distribution of produced W's, is uniquely determined by the underlying noncommuting symmetry that distinguishes Yang-Mills (nonabelian) gauge theories from gauge theories with the more familiar (abelian) gauge symmetry of Maxwellian electrodynamics.

Proposals are under consideration to increase the luminosity of the Fermilab Tevatron collider by an order of magnitude in the mid-1990s, with perhaps another order of magnitude increase by the end of the decade. With the first of these upgrades it has been estimated that the W mass could be measured to ± 100 MeV (up to currently unknown systematic uncertainties that might emerge with higher statistics data), and that the top quark could be discovered if it weighs as much as 160 GeV (*45*). With another factor 10 increase in luminosity the top quark could be discovered even if it were heavier than the $\simeq$250-GeV upper limit based on Eq. 5 (*45*).

The SSC and LHC. The standard model is as important for the questions it enables us to ask as for the questions it answers. It is a special and unexpected triumph of the study of the weak interaction that it has led us to a precise formulation of the problem of the origin of mass. The W and Z bosons are distinguished from their partner the photon by the mass which they are believed to acquire by the Higgs mechanism. The Higgs mechanism may or may not entail the existence of a Higgs boson, but it necessarily requires the existence of a new force and a new set of particles that carry the new force.

A comprehensive search for this new force and its associated quanta will be possible at the Superconducting Super Collider (SSC), to be built near Dallas during the 1990s. With a circumference of 54 miles, the SSC will supplant LEP as our largest scientific instrument. It will provide for high luminosity collisions of two 20 TeV $= 20 \times 10^{12}$ eV proton beams. General arguments based only on gauge symmetry and probability conservation imply that the new force must begin to emerge in the interactions of WW, WZ, and ZZ boson pairs at a scale at or below about 2 TeV (*22*). By measuring the scattering of longitudinally polarized gauge boson pairs with center of mass energy between 1 and 2 TeV, we will learn whether the new force is weak or strong and whether the associated quanta lie below or above 1 TeV. Though it is difficult to conceive of the SSC as minimal in any respect, at design luminosity and energy the SSC will just be sufficient to provide the necessary data (*46*).

The LHC (Large Hadron Collider) is a similar though less powerful collider under consideration for construction in the LEP tunnel. With up to 8-TeV proton beams the LHC would not be capable of exploring the critical region between 1 and 2 TeV in gauge boson pair energy. But the LHC would share with the SSC considerable ability to search for many other possible phenomena. For instance, a heavy neutral Z′ boson predicted in certain grand unified theories could be discovered at the LHC at a mass up to 3 TeV and at the SSC with a mass up to 6 TeV (*47*). Its discovery would allow us to study how the electroweak and strong forces are unified, teaching us about a symmetry that would only be explicitly realized at the unimaginable scale of 10^{15} GeV. Such a discovery would provide an experimental window on the era 10^{-35} seconds after the birth of the universe in the Big Bang when the preponderance of matter over antimatter may have developed according to grand unified theories.

Conclusion

The Z boson occupies a strategically central position in the standard model. The experimental setting for Z decay studies in electron-positron colliders is extremely favorable, being blessed by a large cross section and cleanly observable final states. As such, high statistics studies of Z decays are likely to prove a fountain of important physics. Since the Z outdoes the photon by having direct interactions with all the known quarks and leptons (the photon does not interact directly with neutrinos), its decays are an ideal venue for standard model physics studies and may also provide—especially given a large data sample—the few anomalous events that could turn existing ideas on their heads. High precision measurements of the properties of the Z, requiring again very large numbers of events or fewer events with longitudinally polarized electrons, are another effective means to search for new physics, which by quantum corrections or mixing effects can induce deviations from standard model predictions, even for new physics originating at much larger mass scales than the mass of the Z itself.

The discovery of the neutral-current weak interaction in 1973 completed our picture of the weak force. That discovery verified a crucial prediction of the unified electroweak theory of Glashow, Salam, and Weinberg and presaged the discovery of the Z boson 10 years later when a sufficiently energetic accelerator had been constructed at CERN. Perhaps the most exciting aspect of the electroweak theory is that it is incomplete, but incomplete in a very particular way, requiring the existence of a fifth force of nature and an associated set of new particles to complete it. This is arguably the most important prediction of the theory: that there is a still unknown force of nature which generates the masses of the particles that make up our world. This force might be mediated by Higgs bosons light enough to observe in Z decays. It induces quantum corrections that would be observable in precision measurements of the properties of the Z and W bosons. And its nature is certain to emerge from studies of W and Z boson interactions at the Superconducting Super Collider to be built during the coming decade.

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Research Article

Evidence That the Head of Kinesin Is Sufficient for Force Generation and Motility in Vitro

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Kinesin is a mechanochemical protein that converts the chemical energy in adenosine triphosphate into mechanical force for movement of cellular components along microtubules. The regions of the kinesin molecule responsible for generating movement were determined by studying the heavy chain of *Drosophila* kinesin, and its truncated forms, expressed in *Escherichia coli*. The results demonstrate that (i) kinesin heavy chain alone, without the light chains and other eukaryotic factors, is able to induce microtubule movement in vitro, and (ii) a fragment likely to contain only the kinesin head is also capable of inducing microtubule motility. Thus, the amino-terminal 450 amino acids of kinesin contain all the basic elements needed to convert chemical energy into mechanical force.

EUKARYOTIC CELL FUNCTIONS AND GROWTH REQUIRE INtracellular motility, which is driven by molecular motors such as myosin, dynein, and kinesin (*1, 2*). The nature of the molecular mechanism by which these motors generate force is largely unknown. It is thought that these proteins generate motile force by cyclic cross-bridge interactions with actin filaments or microtubules (*1, 2*). These interactions may be coupled to conformational changes of the motors as a result of adenosine triphosphate (ATP) hydrolysis, converting the chemical energy stored in ATP into mechanical force. However, very little information is available about the way that energy produced by ATP hydrolysis leads to conformational changes of the molecule and what kinds of conformational change lead to motile force production.

Kinesin is a newly discovered cytoplasmic microtubule motor that may function in organelle transport (*3–5*), endoplasmic reticulum extension (*6*), and mitosis (*7*). In vitro, in the presence of ATP,

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