The intent of the fourth experiment is to measure interference effects between the neutral and charged weak currents via scattering experiments with neutrinos and electrons. If destructive interference is detected, then the present electroweak theory should be applicable even at higher energies; if constructive interference is detected, then the theory will need to be expanded, say by including vector bosons beyond those (the Z^0 and the $W^{\pm}$) already in the standard model.

Tritium Beta Decay

In 1930 Pauli argued that the continuous kinetic energy spectrum of electrons emitted in beta decay would be explained by a light, neutral particle. This particle, the neutrino, was used by Fermi in 1934 to account quantitatively for the kinematics of beta decay. In 1953, the elusive neutrino was observed directly by a Los Alamos team, Fred Reines and Clyde L. Cowan, using a reactor at Hanford.

Though the neutrino has generally been taken to be massless, no theory requires neutrinos to have zero mass. The current experimental upper limit on the electron neutrino mass is 55 electron volts (eV), and the Russian team responsible for this limit claims a lower limit of 20 eV. The mass of the neutrino is still generally taken to be zero, for historical reasons, because the experiments done by the Russian team are extremely complex, and because masslessness leads to a pleasing simplification of the theory.

A more careful look, however, shows that no respectable theory requires a mass that is identically zero. Since we have many neutrino flavors (electron, muon and tau neutrinos, at least), a nonzero mass would immediately open possibilities for mixing between these three known lepton families. Without regard to the minimal standard model or any unification schemes, the possible existence of massive neutrinos points out our basic ignorance of the origin of the known particle masses and the family structure of particles.

An Experimentalist's View of the Standard Model

The dream of physicists to produce a unified field theory has, at different times in the history of physics, appeared in a different light. For example, one of the most astounding intellectual achievements in nineteenth century physics was the realization that electric forces and magnetic forces (and their corresponding fields) are different manifestations of a single electromagnetic field. Maxwell's construction of the differential equations relating these two fields paved the way for their later relation to special relativity.

QED. The most successful field theory to date, quantum electrodynamics (QED), appears to have provided us with a complete description of the electromagnetic force. This theory has withstood an extraordinary array of precision tests in atomic, nuclear, and particle physics, and at low and high energies. A generation of physicists has yearned for comparable field theories describing the remaining forces: the weak interaction, the strong interaction, and gravity.

An even more romantic goal has been the notion that a *single* field theory might describe all the known physical interactions.

Electroweak Theory. In the last two decades we have come a long way towards realizing this goal. The electromagnetic and weak interactions appear to be well described by the Weinberg-Salam-Glashow model that unifies the two fields in a gauge theory. (See "Particle Physics and the Standard Model" for a discussion of gauge theories and other details just briefly mentioned here.) This electroweak theory appears to account for the apparent difference, at low energies, between the weak interaction and the electromagnetic interaction. As the energy of an interaction increases, a unification is achieved.

So far, at energies accessible to modern high-energy accelerators, the theory is supported by experiment. In fact, the discovery at CERN in 1983 of the heavy vector bosons W^+, W^-, and Z^0, whose large mass (compared to the photon) accounts for the relatively "weak" nature of the weak force, beautifully confirms and reinforces the new theory.

The electroweak theory has many experimental triumphs, but experimental physicists have been encouraged to press ever harder to test the theory, to explore its range of validity, and to search for new fundamental interactions and particles. The experience with QED, which has survived decades of precision tests, is the standard by which to judge tests of the newest field theories.

QCD. A recent, successful field theory that describes the strong force is quantum chromodynamics (QCD). In this theory the strong force is mediated by the exchange of color gluons and a coupling constant is determined analogous to the fine structure constant of the electroweak theory.

Standard Model. QCD and the electroweak theory are now embedded and united in the minimal standard model. This model organizes all three fields in a gauge

Table

The first three generations of elementary particles.

Family:		I	II	III
Doublets	Quarks:	$\begin{pmatrix} u \\ d \end{pmatrix}_L$	$\begin{pmatrix} c \\ s \end{pmatrix}_L$	$\begin{pmatrix} t \\ b \end{pmatrix}_L$
	Leptons:	$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L$	$\begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L$	$\begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L$
Singlets:		$u_R, d_R, e_R,$	$c_R, s_R, \mu_R,$	t_R, b_R, τ_R

theory of electroweak and strong interactions. There are two classes of particles: spin-½ particles called fermions (quarks and leptons) that make up the particles of ordinary matter, and spin-1 particles called bosons that account for the interactions between the fermions.

In this theory the fermions are grouped asymmetrically according to the "handedness" of their spin to account for the experimentally observed violation of CP symmetry. Particles with right-handed spin are grouped in pairs or doublets; particles with left-handed spin are placed in singlets. The exchange of a charged vector boson can convert one particle in a given doublet to the other, whereas the singlet particles have no weak charge and so do not undergo such transitions.

The Table shows how the model, using this scheme, builds the first three generations of leptons and quarks. Since each quark (u, d, c, s, t, and b) comes in three colors and all fermions have antiparticles, the model includes 90 fundamental fermions.

The spin-1 boson mediating the electromagnetic force is a massless gauge boson, that is, the photon γ. For the weak force, there are both neutral and charged currents that involve, respectively, the exchange of the neutral vector boson Z^0 and the charged vector bosons W^+ and W^-. The color force of QCD involves eight bosons called gluons that carry the color charge.

The coupling constants for the weak and electromagnetic interactions, g_{wk} and g_{em}, are related by the Weinberg angle θ_W, a mixing angle used in the theory to parametrize the combination of the weak and electromagnetic gauge fields. Specifically,

$$\sin\theta_W = g_{em}/g_{wk} .$$

Only objects required by experimental results are in the standard model, hence the term minimal. For example, no right-handed neutrinos are included. Other minimal assumptions are massless neutrinos and no requirement for conservation of total lepton number or of individual lepton flavor (that is, electron, muon, or tau number).

The theory, in fact, includes no mass for *any* of the elementary particles. Since the vector bosons for the weak force and all the fermions (except perhaps the neutrinos) are known to be massive, the symmetry of the theory has to be broken. Such symmetry-breaking is accomplished by the Higgs mechanism in which another gauge field with its yet unseen Higgs particle is built into the theory. However, no other Higgs-type particles are included.

Many important features are built into the minimal standard model. For example, low-energy, charged-current weak interactions are dominated by $V-A$ (vector minus axial vector) currents; thus, only left-handed $W^{\pm}$ bosons have been included. Also, since neutrinos are taken to be massless, there are supposed to be no oscillations between neutrino flavors.

There are many possibilities for extensions to the standard model. New bosons, families of particles, or fundamental interactions may be discovered, or new substructures or symmetries may be required. The standard model, at this moment, has no demonstrated flaws, but there are many potential sources of trouble (or enlightenment).

GUT. One of the most dramatic notions that goes beyond the standard model is the grand unified theory (GUT). In such a theory, the coupling constants in the electroweak and strong sectors run together at extremely high energies (10^{15} to 10^{19} giga-electron volts (GeV)). All the fields are unified under a single group structure, and a new object, the X, appears to generate this grand symmetry group. This very high-energy mass scale is not directly accessible at any conceivable accelerator. To explore the wilderness between present mass scales and the GUT scale, alas, all high-energy physicists will have to be content to work as low-energy physicists. Some seers believe the wilderness will be a desert, devoid of striking new physics. In the likely event that the desert is found blooming with unexplored phenomena, the journey through this terra incognita will be a long and fruitful one, even if we *are* restricted to feasible tools. ■