Neutrinos

and Grand Unified Theories

Today many particle theorists believe that three of the known fundamental interactions-the strong, the electromagnetic, and the weak-are but different facets of one "grand unified" theory of interactions. How close we have come to this ancient goal of unification is demonstrated by the fact that there are now only several candidates for such a theory. Which, if any, is correct must still be decided by experiment.

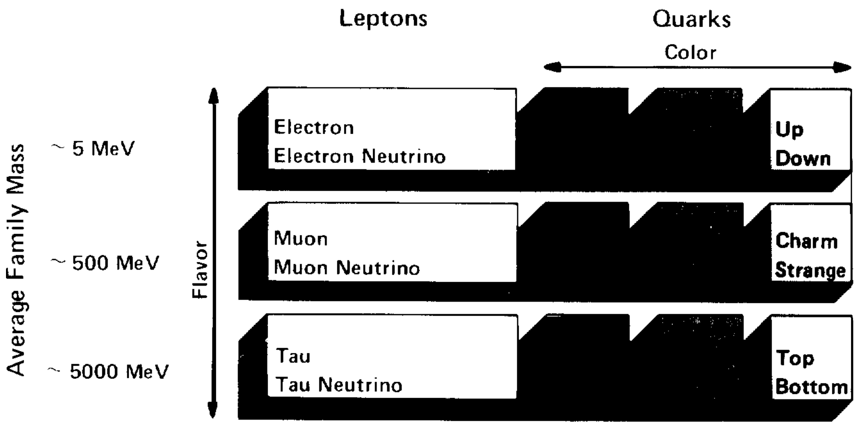
All the proposed grand unified theories build on the observation that the quarks (the components of those particles, such as the neutron and the pion, that interact through the strong force) and the leptons (the particles, such as the electron and the muon neutrino, that do not interact through the strong force) can be arranged by increasing mass into three families. The electron and its neutrino, the muon and its neutrino, and the tau and its neutrino are paralleled by the up and down quarks, the strange and charmed quarks, and the top and bottom quarks. In grand unified theories this parallel structure, or symmetry, between quarks and leptons is given a dynamic origin by postulating a new interaction that can change quarks into leptons and vice versa.

According to these new theories, our division of fundamental forces into strong, electromagnetic, and weak is merely a consequence of the energies at which we have observed particle interactions. At much higher energies, beyond any we can hope to achieve in the laboratory, the distinctions disappear: all three forces become components of a single force, and leptons and quarks become indistinguishable from each other. This symmetry between leptons and quarks is broken at energies accessible in the laboratory, energies at which quarks participate in strong interactions but leptons do not.

The grand unification of interactions and also the mechanism for breaking the symmetry are expressed mathematically in non-Abelian gauge field theories. These theories are a generalization of the familiar Abelian gauge theory for electromagnetic interactions known as quantum electrodynamics.

As in quantum electrodynamics, particles interact through the exchange of quantum excitations of the gauge fields. In quantum electrodynamics, the exchange particle is the photon. In grand unified theories, the exchange particles are called gauge vector bosons. All these vector bosons would be massless, like the photon, were it not for the fact that the gauge symmetry is partially broken by the effects of Higgs bosons. These massive scalar particles are introduced into the theory to provide a background field that breaks the symmetry just as the magnetic field breaks the rotational symmetry in a ferromagnetic domain. Higgs boson effects are also responsible for nonzero quark and lepton masses.

As a result of the symmetry breaking, the leptoquark gauge bosons that turn quarks into leptons acquire extremely large masses, Theoretical predictions for the leptoquark mass range from 10^5 GeV in Pati-Salam type models to 10^{15} GeV for models that have



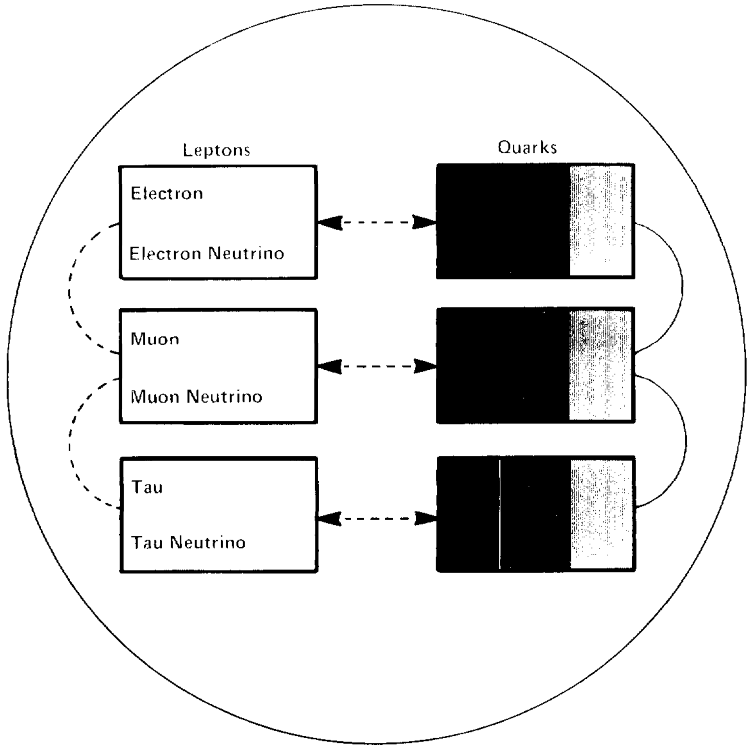
Quarks and leptons are now considered to be the fundamental constituents of matter. They are here arranged horizontally according to color quantum number and vertically according to flavor quantum number. Quarks come in three colors —red, green, and blue. Each color represents a different strong-interaction "charge." Leptons do not participate in strong interactions and thus have no color. Quarks and leptons are each assigned one of six flavor quantum numbers. The six flavors have been grouped into three pairs corresponding to three families of quarks and three families of leptons. The families have then been arranged by increasing average rest mass. This arrangement suggests the existence of three larger families, each one made up of quarks and leptons. Our everyday world is composed entirely of the lightest of these three quark-lepton families. The proton, for example, consists of two up quarks and one down quark; the neutron consists of two down quarks and one up quark. The other two families appear to be more massive imitations of the first family.

SU(5), 0(10), or E_6 symmetry, At energies greater than the leptoquark mass the distinction between quarks and leptons vanishes and the symmetry of grand unified **theories becomes** apparent. Such energies cannot, however, be achieved in foreseeable experiments. The required accelerators based on present technology would be larger than the solar system! Therefore, we must find indirect tests of the symmetries and **new** interactions predicted by grand unified theories.

Almost all of these theories offer at least one such test: they predict that protons undergo radioactive decay and hence that no element is perfectly stable. (The exceptions have been contrived specifically to avoid this.) Proton decay was previously believed to be impossible; it was prohibited by negative observations that had been elevated to a principle called baryon-number conservation, However, the large value of the leptoquark mass severely suppresses the rate of proton decay and makes grand unified theories consistent with the observed stability of the proton and the apparent conservation of baryon number. At the same time, grand unified theories make fairly precise predictions for the proton decay rate. Experimental searches for this decay, sensitive at the appropriate level, are now underway.

Most of these theories also have as a consequence another previously dismissed possibility-that neutrinos have a nonzero rest mass. Again one can contrive theories that avoid this, but the natural structures that appear produce neutrino masses in a fashion similar to that by which masses are produced for quarks and charged leptons. There is, moreover, simply no reason for neutrinos to be massless, and so the converse is to be expected. Furthermore, since the quarks (down, strange, and bottom) are

Grand unified theories incorporate the observed family structure of fundamental particles in a natural way. Each family is a separate realization of a single representation of the unifying symmetry group. These theories not only organize the particles into families, but also predict new interactions between quarks and leptons within a family. Leptoquarks (massive vector bosons) change leptons into quarks and vice versa. At very high energies, leptons and quarks become indistinguishable. In addition, Higgs bosons effect mixing across *family lines. Such mixing has been observed between strange and down quarks and between bottom and strange quarks. In the context of grand unification, similar mixing between lepton families seems likely. Neutrino oscillation would be evidence for such mixing. (An indirect route for neutrino mixing is indicated by the yellow lines.)*



Legend:

Conjectured quark-lepton transformation within a family by leptoquarks

----- Conjectured neutrino mixing between families by Higgs boson effects

Observed quark mixing between farmilies reflected in grand unified theories by Higgs boson effects

Alternate route for neutrino mixing between families

known to be mixed by mass effects, it is likely that the different neutrino types undergo a similar mass mixing. The existence of leptoquarks and the known quark mixing provide a route for lepton mixing (albeit by a very small amount).

Explicit calculations for specific models yield neutrino mass values no larger than a few tens of electron volts for the heaviest (tau) neutrino. This is close to the present experimental limit for those neutrinos that accompany electrons in beta decay (but these need not be pure electron antineutrinos if mixing occurs) and very close to the value suggested by astrophysical arguments. The results of a recent experiment on beta decay of tritium have been interpreted as evidence for a neutrino mass between 15 and 45 eV.

Exciting as is the prospect of determining another property of the neutrino, the implications for grand unification add even more impetus to the search. The pattern of mass values and the values of mixing parameters will give vital clues about details of the Higgs bosons in a correct grand unified theory. Although much of the structure of this theory is fixed by the gauge symmetry principle, a number of Higgs bosons are introduced into the theory to provide quarks and leptons with their known masses. There is even one set of Higgs bosons that can only be observed indirectly by determining the nature of the neutrino masses it generates.

Thus, while the enormous energy scales involved most probably rule out direct experimental tests of grand unified theories, low-energy measurements of neutrino masses and mixings in oscillation experiments will provide a window on the most basic laws of our universe ■