Beyond Truth and Beauty: A Fourth Family of Particles

Three families of the fundamental particles called quarks and leptons are known. Recent experiments hint that there is one more family, but there are probably no more than five

by David B. Cline

Physicists who study the fundamental nature of matter have a faith that the diversity of the physical universe can be explained by assuming the existence of a few fundamental particles. It is a faith that has been sorely tried. In the middle years of this century the emerging simplicity of the proton, neutron and electron and their antimatter counterparts dissolved into hundreds of subnuclear particles. In the 1970's simplicity seemed to reemerge with the discovery of the quark, only to apparently unravel again as several other quarks appeared.

Now the tide of battle may be turning toward a compromise agreement. On the one hand, observations of the isotopes deuterium and helium in deep space, coupled with laboratory accelerator experiments, now indicate that the number of fundamental particles is indeed limited. On the other hand, there are some hints that this number may include more than the three families of quarks now known to exist. Stoking the excitement is the prospect that answers to profound questions such as the origin of mass may be within the reach of sophisticated new accelerators that are just beginning to operate.

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To understand why some physicists think a fourth family of quarks may exist, but that there are not many more than four, one must first understand what is currently explained and unexplained by the standard model of particle physics. Almost every field has its standard model; the standard model in particle physics is based on the assumption that ordinary matter is composed of two types of particles, quarks and leptons, and that the forces between them are transmitted by a third category of particles called bosons. Leptons include the familiar electron and neutrino; the less familiar quarks combine to make up such large particles as the proton and the neutron. An example of a boson is the common photon, which transmits the electromagnetic force.

Three families of quarks have been discovered experimentally, each consisting of two particles, making a total of six quarks. The first family consists of the "up" quark and the "down" quark. The up quark has a mass of approximately four million electron volts (MeV), or about 1/250th the mass of the proton (which is close to a billion electron volts, or 1 GeV). The mass of the down quark is slightly greater—about 7 MeV. The second family consists of the "strange" quark and the "charm" quark, with masses of about 150 MeV and about 1,300 MeV respectively. The third family consists of the "bottom" quark, known in civilized parts of the world as "beauty," with a mass of 5.5 GeV, and the "top," or "truth," quark—which has yet to be discovered [*see bottom illustration on page 62*].

Whereas a proton has one unit of positive electric charge, quarks have fractional charge. An up quark has a fractional charge of 2/3 and a down quark has a charge of −1/3. A proton consists of two ups and a down, giving the required total charge of 1. The neutron is composed of two downs and an up for a total electric charge of zero. In a similar manner the various quarks can be combined to form all the other known particles that are not leptons or bosons.

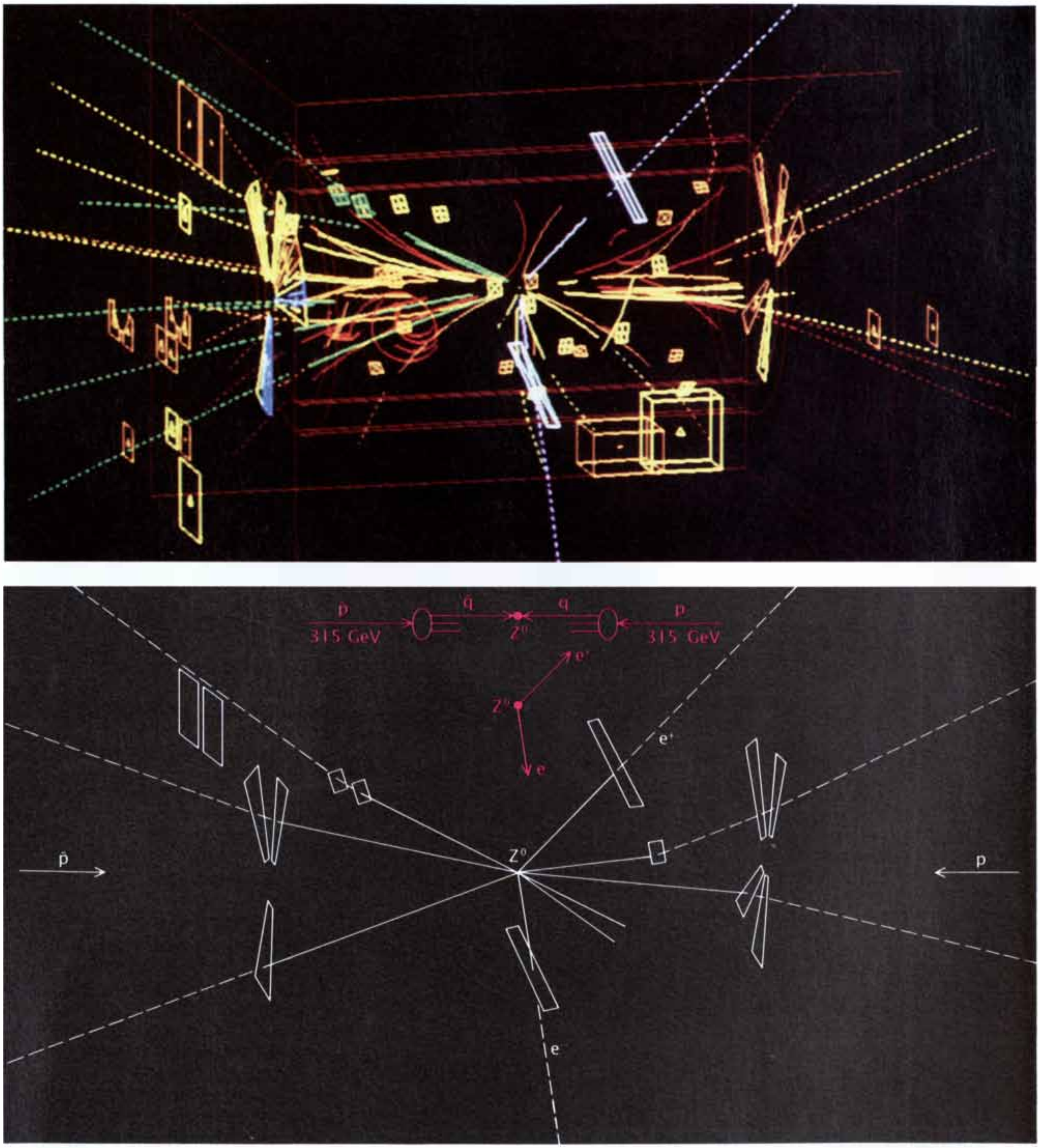
Each family of quarks is roughly 10 times as massive as the preceding family. This fact suggests that any new quarks will be very massive. Indeed, recent experiments at CERN, the European laboratory for particle physics, set a lower limit of about 50 GeV for the mass of the undiscovered truth quark. In each family, however, the quark masses lie within an order of magnitude of each other, and so physicists expect the truth quark to have a mass not more than 10 times the mass of the beauty quark. (If future accelerator experiments produce a very massive truth quark, theorists will begin to scratch their heads.)

The Lepton Families

Experimentally, it turns out that every family of quarks is associated with a family of leptons, each consisting of a charged lepton and a neutral one. In the first family the charged lepton is the electron and the neutral one is the electron neutrino; in the second family the leptons are the muon and the mu neutrino, and in the third family they are the tauon and the tau neutrino.

Compared with quarks, leptons are extremely light [*see illustration on page 63*]. The electron has a mass of approximately 1/2 MeV; observations of electron neutrinos from the supernova 1987A limits their mass to less than about 16 electron volts. The reasoning is that the velocity of particles having a nonzero rest mass varies with their energy, so that one would expect the arrival time of a burst of massive neutrinos to be spread over a finite period. The fact that the 1987 supernova neutrinos all arrived at the earth within 13 seconds of one another results in the 16 eV limit. And since this is only an upper limit, the real electron-neutrino mass could be zero.

The charged lepton of the second family, the muon, is about 200 times as massive as the electron but is otherwise identical. Experimental limits on the mu neutrino's mass require it to be less than about 100,000 eV. Cosmological limits are much more stringent than this, however; they require that the mass of any neutrino be below the minuscule value of 65 eV. The

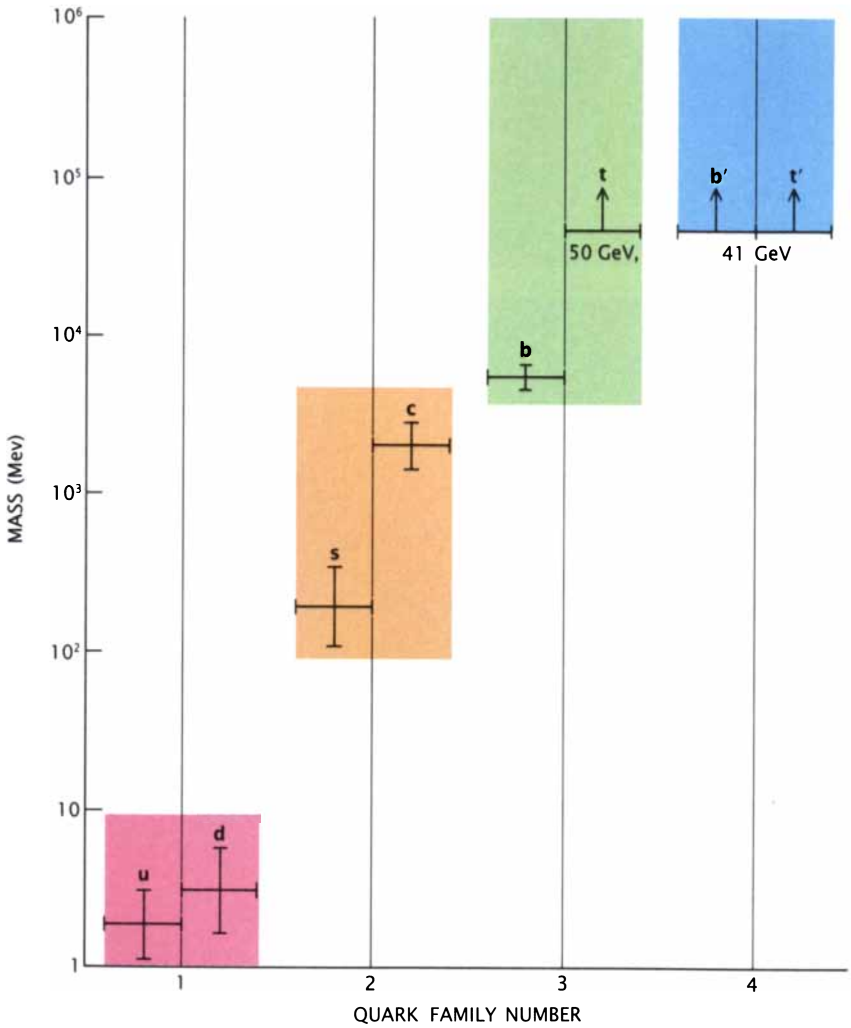


PRODUCTION AND DECAY of a neutral intermediate vector boson (Z^0 particle) are shown in a computer image, along with a drawing identifying the events. The Z^0 was produced by quark-antiquark collisions in the UA1 experiment at the proton-antiproton collider at CERN, the European laboratory for particle physics; the particle decays into an electron-positron pair. (Other tracks are those of other particles formed by the colliding beams.) The Z^0 can decay into all existing lepton families, including neutrinos. If there were an infinite number of neutrino families, the decay of the Z^0 into the electron-positron pair would never be seen. The fact that it is seen, with high probability, limits the number of neutrino families to five.

FAMILY	1	2	3	NOT YET DETECTED 4
LEPTONS	$\binom{\nu_e}{e^-}$	$\binom{\nu_\mu}{\mu^-}$	$\binom{\nu_\tau}{\tau^-}$	$\binom{\nu_L}{L}$
QUARKS	$\binom{u}{d}$	$\binom{c}{s}$	$\binom{t}{b}$	$\binom{t'}{b'}$

GAUGE BOSONS: PHOTON, GLUON, $W^{\pm}$, Z^0, GRAVITON | HIGGS SCALAR

STANDARD MODEL of particle physics assumes that matter is composed of quarks and leptons and that forces are transmitted by bosons. Each lepton family consists of a charged lepton and a much lighter neutral one, successively the electron (e^-) and electron neutrino (ν_e), the muon (μ) and mu neutrino (ν_μ) and the tauon (τ) and tau neutrino (ν_τ). According to the standard model, each lepton family is associated with a quark family consisting of two particles: an "up" (*u*) and a "down" (*d*) quark; a "strange" (*s*) and a "charm" (*c*) quark; a "bottom" (*b*) quark and a "top" or "truth" (*t*) quark. The truth quark has not yet been detected. If the pairing of the families continues to a fourth generation, one would expect to find a fourth charged lepton (*L*) and a fourth neutrino (ν_L), as well as two more quarks, labeled here *t′* and *b′*.



MASSES of the five known quarks are given in millions of electron volts (MeV). The masses of the quarks in successive families differ by about an order of magnitude. Experimental limits on the truth quark put its mass above 50 GeV (billions of electron volts); limits on the fourth-family quarks put their masses above 41 GeV.

tau neutrino has not yet been directly observed, but its partner the tauon was discovered in 1976 by Martin L. Perl and his colleagues at the Stanford Linear Accelerator Center (SLAC). The particle has a mass of 1.8 GeV. Since theory requires that the tauon have its own neutrino, physicists are confident that the tau neutrino exists. Direct experiments put the mass of the tau neutrino at less than 70 MeV; again the cosmological limit appears to be below 65 eV.

Like the quark families, the lepton families are clumped into different mass ranges. The mass of the muon is approximately two orders of magnitude greater than that of the electron, and the tauon in turn is about 20 times more massive than the muon. One might expect, then, that any additional charged leptons will have a mass in the vicinity of 40 GeV. As I shall show below, current experimental lower limits for new charged lepton masses are consistent with this prediction. The neutrino masses may also be spaced at large intervals, but because only upper limits are established, all that can now be said is that the mass of neutrinos is very small compared with the mass of their charged partners.

The smallness of the neutrino mass points to the second major difference between quarks and leptons: apart from the fact that leptons are much lighter in absolute terms than their associated quarks, the mass ratios within quark families are much smaller than those within the associated lepton families. Within each quark family the ratio of quark masses is no greater than about 10. The mass ratio of the down quark to the up quark, for example, is about two. The leptons present quite a different picture: given the upper limits on neutrino masses, the mass ratio of the electron to the electron neutrino is about 10,000; if the neutrino were to turn out to be massless, the ratio would be infinite.

The standard model has also been successful in describing the bosons, the particles that transmit forces between other particles. In Maxwell's theory of electromagnetism this role is played by the photon, which transmits the electromagnetic force. The present standard model contains the weak force, which governs radioactive decay, and the strong force, which binds the nucleus. Therefore other bosons are required. Weak interactions (such as the decay of a neutron into a proton and an electron) that involve the exchange of electric charge are governed by the so-called charged intermediate vector boson, or W. Other weak interactions, which do not require an exchange of charge, are mediated by the neutral intermediate vector boson, or Z^0. One of the great triumphs of the standard model was the prediction of the masses of the W and the Z^0 particles. Both particles were subsequently discovered at CERN in 1983—at the expected masses. All other observed properties of the particles are also in remarkable agreement with the theory.

Defects in the Model

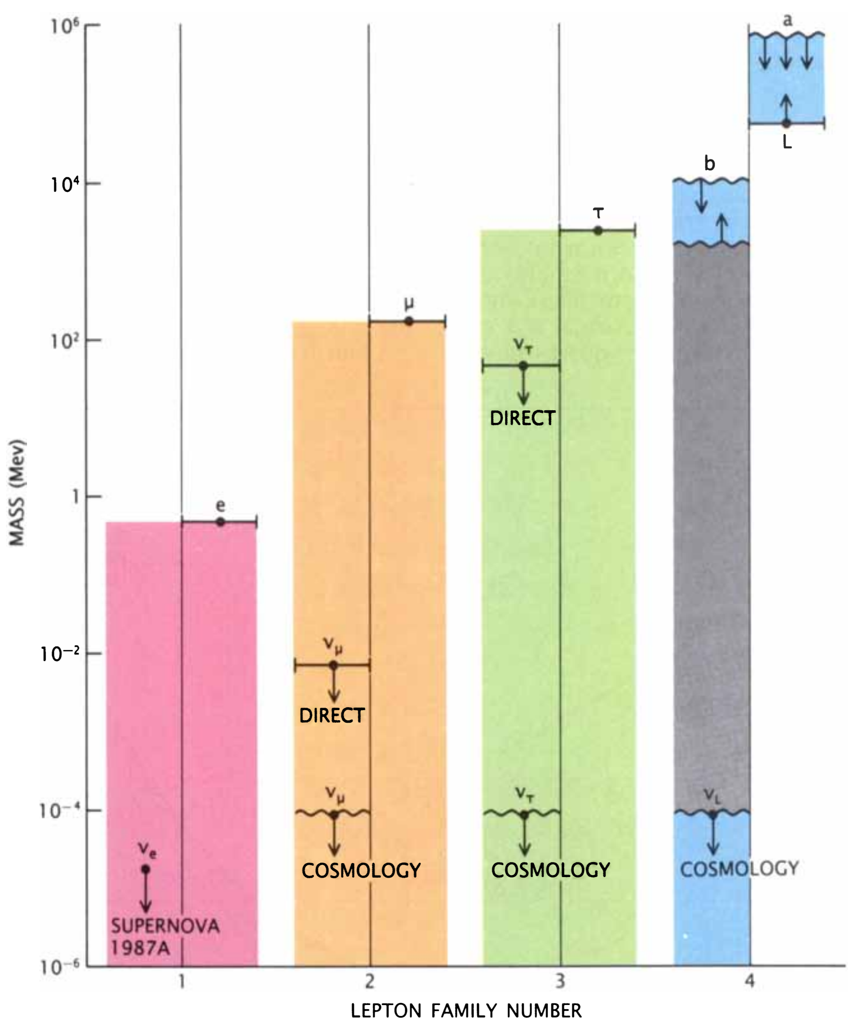
In spite of such successes, the standard model has a number of serious defects. To begin with, it does not prescribe the number of families of quarks and leptons at all. Why are there at least three families, given that only the first family is needed to make up the ordinary protons, neutrons and electrons in the universe? Or, as I. I. Rabi put it 50 years ago, "The muon, who ordered that?"

The standard model also fails to predict the mass of all the remaining particles; the 50-GeV lower limit on the mass of the truth quark is an experimental result, and no one knows what the upper limit is. Nor does the model explain the hierarchy of quark and lepton masses described above. Why are the families separated by roughly an order of magnitude in mass for quarks and two orders of magnitude for leptons? Why are the ratios of quark masses within a family so small and the ratios of lepton masses so large? Many numerological attempts have been made over the years to explain this mass spectrum, but none has met with any success, and this is one of the great unexplained whys of the standard model.

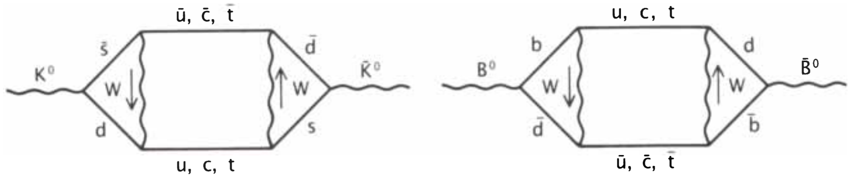
Questions relating to the number of families, mass and mass hierarchies are not the only ones left unanswered by the standard model. Another major mystery is the fact that whereas different kinds of quarks are often observed to transform into one another, leptons are never observed to do so. For example, the charm quark may decay into a strange quark and a particle known as a "virtual W" (which can be thought of as a real W with such a short lifetime that it cannot be directly observed). On the other hand, no muon has ever been seen to decay into an electron and a photon, and the probability of its happening has now been experimentally reduced to less than one part in 100 billion.

This proliferation of mysteries has led some theorists to suspect the existence of a fourth family of quarks and leptons. The discovery of such a family might clear up some long-standing questions. One of them has to do with the phenomenon known as charge-parity violation, which is itself related to the quark-quark transition probabilities just discussed. Until the 1960's physicists had assumed that measurable properties of any physical system should remain unchanged when each particle is transformed into its antiparticle and the system is reflected in a mirror. Because the operation of changing a particle into its antiparticle requires changing its charge, and because mirror-reflection is known as parity reversal, the statement that any system should remain unaltered under these combined operations is known as the law of charge-parity invariance.

The cherished belief in CP invariance fell in 1964, when Val L. Fitch, James W. Cronin, James H. Christenson and René Turlay of Princeton University were investigating the decay rate of a particle known as the neutral K meson, or kaon. The kaon usually decays into three other particles (into three pions, for example); such a transition is consistent with the law of CP invariance. The Princeton experiment showed, however, that about once in every 500 times the kaon decays into only two pions—a transition that vio-



LEPTON MASS SPECTRUM shows that the masses of charged leptons, like those of quarks, are hierarchical: the tauon mass is roughly an order of magnitude greater than the muon mass, which in turn is roughly two orders greater than the electron mass. Limits on the mass of the fourth charged lepton (L) require that it be greater than 41 GeV. The mass difference between the W and Z^0 vector bosons supplies an upper limit (*a*). The masses of the three neutrinos are not known. Upper limits from supernova 1987A put the electron-neutrino mass at less than 16 electron volts. The requirement that no neutrino be so massive as to noticeably decelerate the expansion of the universe sets a 65-eV "cosmology" upper limit for all neutrinos. The gray area (*right*) is excluded by theory; limit *b* comes from dark-matter searches.



FEYNMAN DIAGRAMS show flavor mixing for the kaon (K^0) system (*left*) and a *B*-meson system (*right*). Mixing takes place when a K^0, which consists of an antistrange ($\bar{s}$) quark and a down (d) quark, turns into an antikaon ($\bar{K}^0$). This requires that the $\bar{s}$ turn into a $\bar{d}$ and the d into an s. In this *B*-meson system, consisting of a b and a $\bar{d}$, the b must transform into a d and the $\bar{d}$ into a $\bar{b}$. The transitions are called cross-family or flavor-mixing transitions. Such mixing is needed for charge-parity violation.

lates CP invariance. As a result of experiment, then, a supposed law of nature was thrown out—even though the actual origin of CP violation in the kaon system remains unexplained today and is considered one of the great mysteries in physics.

Flavor Mixing

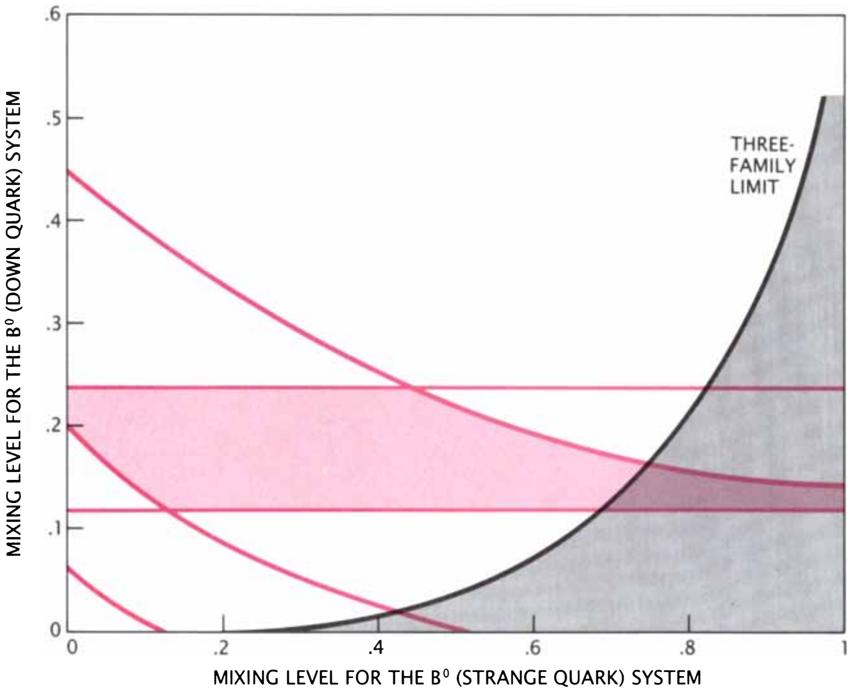
Unexplained though CP violation may be, its magnitude can be linked to quark-quark transition probabilities. Usually quarks transform into other members of their own family, as in the decay of a charm quark into a strange quark and a virtual *W*. For CP violation to take place, quarks must be able to transform into members of other families, a process known as flavor mixing (because quark families are whimsically characterized as having distinct flavors). Moreover, it can be shown that a two-family standard model would not be enough to allow CP violation in the neutral kaon system; at least three families of quarks are necessary. Indeed, the existence of CP violation was the first evidence for a third quark family. The amount of CP violation depends on the probability with which a quark from one family can transform into a quark from another family, that is, on the extent of the mixing.

A fourth family would influence the amount of flavor mixing by allowing more quark-quark transitions. Recently physicists at the Deutsches Elektronen-Synchrotron (DESY) and CERN have found that flavor mixing in the *B*-meson system is 20 times as large as expected. The *B* meson is so called because it consists of a beauty quark and one other quark—for example, an antidown quark. In the mixing process the *B* meson is transformed into an anti-*B*, which requires that the beauty quark be transformed into a down and the antidown into an antibeauty [*see top illustration on this page*]. Note that, as in the kaon system, these are flavor-mixing transitions. The rate at which the mixing occurs depends on all existing quarks, as well as on their masses: the more quarks there are, the more mixing is expected to take place. The fact that the mixing discovered at DESY was much larger than expected may indicate that a fourth family of quarks was contributing to it. Because the mass of the truth quark is not yet known, however, it may be that the results can still be accommodated with three quark families.

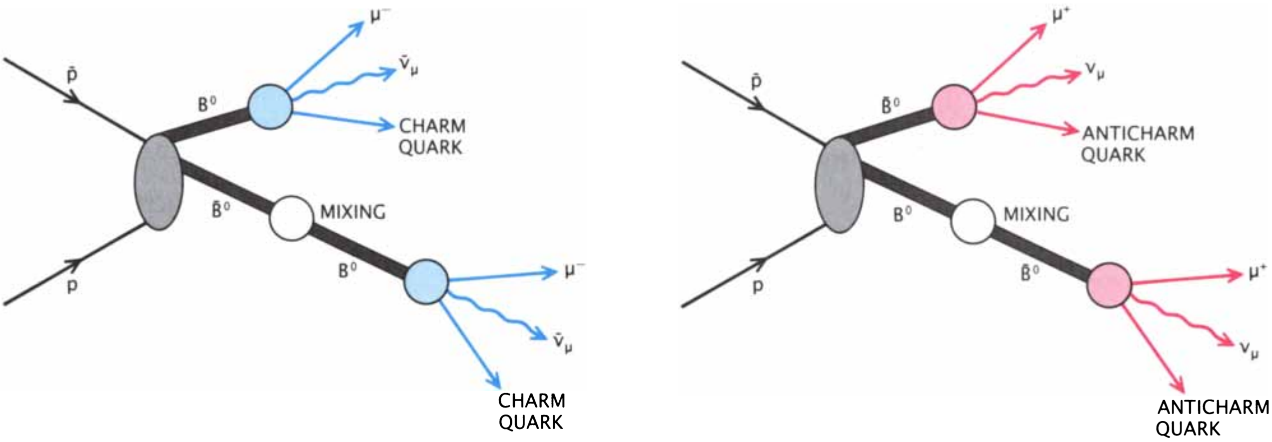
B-meson mixing could also provide insight into the origin of CP violation itself, which until now has been observed only in the neutral kaon system. Flavor mixing is a necessary condition for CP violation, but it is not sufficient. Although CP violation has not yet been detected in *B* mesons, the very size of the mixing has made some investigators optimistic that observation of CP violation in the *B*-meson system cannot be far behind. If CP violation is found to be similarly large, it is unlikely that the three-family standard model will be able to accommodate it (unless the mass of the truth quark is unexpectedly large), and so a fourth family of quarks will have to be invoked.

An experimental test of that proposition should be possible in the near future. Proton-proton collisions in an accelerator can produce *B*-meson–*B*-antimeson pairs, which in turn will decay into products containing two charged leptons. These charged leptons might be electrons or positrons. If CP is conserved, the rates at which mesons decay into electrons and into positrons should be the same; if CP is violated, the decay rates will differ. This test will be extremely sensitive to the existence of a fourth quark family. An observation of CP violation would uniquely relate CP violation to quark transition probabilities and could lead to identification of the fundamental origin of CP violation in nature.

The importance of detecting charge-



MIXING EXPERIMENTS may provide evidence for a fourth family of quarks. B^0 mesons come in two varieties, either a $b\bar{d}$, as in the preceding illustration, or a $b\bar{s}$. Both types undergo flavor mixing, that is, they change into their antiparticles. Recently five experiments (*colored curves*), done at CERN, DESY, SLAC and Cornell University, have shown the mixing was much larger than expected. The colored area delimited by the experimental results indicates the most probable values of the mixing level for the two types of B^0 particles. Most of that area lies beyond the limit allowed by a three-family standard model, indicating that a fourth family may contribute to the mixing.

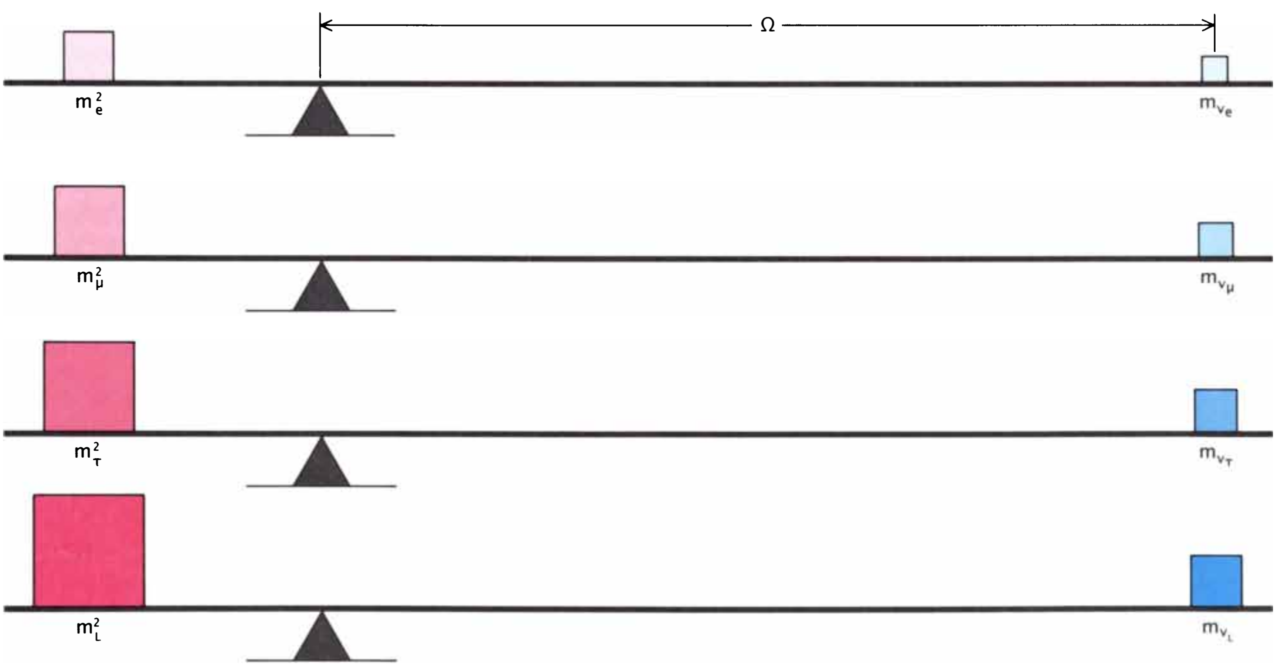


B-MESON DECAY may exhibit charge-parity violation. Proton-proton collisions in an accelerator produce meson-antimeson pairs. A B^0 may decay through flavor mixing into a $\bar{B}^0$, as is shown at the left, or vice versa, as is shown at the right. These particles thereupon decay further into muons, antimuons, quarks and neutrinos. If the decay rate into muons (*left*) differs from the decay rate into antimuons (*right*), then CP is violated. (Note: Charge is conserved here; add the diagrams.)

parity violation in the *B*-meson decay system is leading to the design of a new type of electron-positron collider called a linear-collider *B*-meson factory. Studies of such a machine are in progress at the University of California at Los Angeles and in Italy. The goal is to produce more than a billion beauty quarks and antiquarks per year.

The other major mystery that might be solved by invoking a fourth family is the origin of the particle-mass hierarchy. The hope is that the fourth family is a special case, and that the masses of the first three families are "generated" by interactions with the fourth. This concept, first described by Harald Fritzsch of the University of Munich, relates the mass difference between quarks to an assumed relation between quark mass and quark transitions. So far all observational data are consistent with the Fritzsch model.

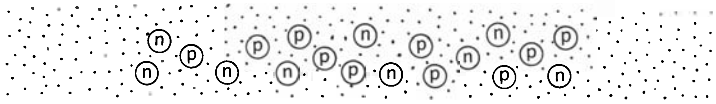
Fritzsch also suggests that the mass ratio of the two new quarks will be four. That is the ratio of the squares of the quark charges—$(2/3)^2/(-1/3)^2$—that would be expected if the electro-



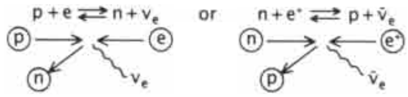
SEESAW MECHANISM proposes that the mass of each neutrino (m_ν) is related to the mass of its associated charged lepton (m) by the formula $m_\nu = m^2/\Omega$; Ω is an unknown mass scale, visualized here as the lever arm of the seesaw. Since, for example, the electron-neutrino mass is known to be less than 16 eV and the electron mass is known to be .5 MeV, the seesaw equation requires Ω to be at least 16 GeV. The tauon mass is 1.8 GeV and cosmological limits on the tau neutrino make it less than 65 eV. Running the seesaw equation with these values gives the stricter lower limit on Ω of 5×10^7 Gev. If Ω is related to a large fourth-lepton mass, the seesaw mechanism shows how this large mass could generate the very small neutrino masses.

BIG-BANG HELIUM PRODUCTION AND NEUTRINO FAMILIES

1. Assume that the universe consists only of neutrons (*n*) and protons (*p*), with a vastly larger background of electrons (e^-), positrons (e^+), neutrinos and antineutrinos ($\nu_e, \nu_\mu, \nu_\tau, \bar{\nu}_e, \bar{\nu}_\mu, \bar{\nu}_\tau$) and photons ($\gamma$), all indicated below by dots. At times much less than one second after the big bang and temperatures much higher than 10^{10} degrees Kelvin, the *n* and *p* appear in almost equal numbers:

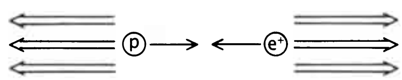


2. Neutrons and protons are constantly transmuted into one another by the so-called weak nuclear reactions:



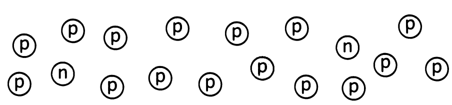
3. Because neutrons are slightly more massive than protons, they are energetically more difficult to produce, and so the *n-p* transmutations in step (2) result in slightly more protons. As the universe expands and cools, less and less energy is available to produce neutrons, and so the weak reactions result in ever more protons. At about one second after the big bang and a temperature of about 10^{10} degrees K. protons outnumber neutrons by about five to one:

4. At this time the expansion rate of the universe overtakes the ever slowing weak-reaction rates, so that collisions between particles essentially cease:

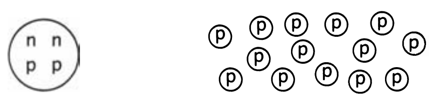


No more neutrons are converted into protons; the 1:5 ratio is "frozen out."

5. Neutrons are radioactive and decay into protons. The lifetime of the neutron is about 15 minutes, so that after three minutes or so about one-third of the neutrons have decayed into protons, leaving one *n* for every eight *p*:



6. At three minutes after the big bang the temperature has dropped to about 10^9 degrees K., which is low enough so that the nucleus of the isotope deuterium (*n,p*) can stay bound. Deuterium is then rapidly processed into helium (2*n*,2*p*). Since helium requires equal numbers of *p* and *n*, helium formation ceases when all the available neutrons are used up:



Since neutrons and protons are of almost equal mass, about 4/16, or 25 percent, of the mass of the universe ends up in helium, with 75 percent left over in protons (hydrogen nuclei).

7. The more families of neutrinos there are, the faster is the expansion rate of the universe. Step (4) therefore occurs earlier and at a higher temperature when more neutrons are present; steps (5) and (6), then, proceed in the presence of more neutrons, resulting in the formation of more helium. Astronomical observations, however, limit helium to less than 25 percent of the mass of the universe. This in turn indicates that there are no more than four neutrino families.

magnetic interaction gives rise to the mass of the quarks.

Several theorists think a new quark should exist in the vicinity of 246 GeV. One of the notable features of the standard model is its prediction that at high enough energies the various forces begin to unify. In particular, the electromagnetic force and the weak and strong nuclear forces should become a single "grand unified" force. The forces should be unified at the incredible energy of 10^{15} GeV, considerably beyond what can ever be attained by an accelerator on the earth. The extrapolation of measured values of fundamental parameters from low energies to the grand-unified energy scale would require the existence of a new massive quark for consistency.

Furthermore, it turns out that the measured values for the *W* and Z^0 masses can provide limits on the mass difference between the two members of the fourth quark family. Present data show that the mass difference between the two quarks of the fourth family should be less than 180 GeV. Hence if one member of the family does exist in the vicinity of 246 GeV, the mass of the other member should lie either at 426 GeV or at about 66 GeV, the latter being well within the range to be searched by accelerators in the near future.

Neutrino Masses

If the fourth family of quarks exists, what are its lepton relatives like? Here the interest centers on the neutrino masses. The cosmological limits mentioned above require the neutrinos to have a mass less than 65 eV—which includes zero. When compared with the mass of the *W*, this gives a mass ratio of one billion. What accounts for the incredibly small neutrino mass? There are two different viewpoints: either the neutrino mass is exactly zero as the result of some undiscovered fundamental principle, or the small neutrino mass is a consequence of another very large mass.

The latter viewpoint depends on what is known as the seesaw mechanism, which has been proposed by Murray Gell-Mann of the California Institute of Technology, Pierre M. Ramond of the University of Florida and Richard C. Slansky of the Los Alamos National Laboratory. The disadvantage of the seesaw mechanism is that it is ad hoc; the advantage is that the mechanism is extremely simple. It assumes that the electron-neutrino mass is equal to the square of the electron mass divided by some large unknown mass scale. The electron mass is fixed. Therefore the larger the unknown mass scale, the smaller the resulting neutrino mass; hence the name seesaw [*see bottom illustration on page 65*].

To illustrate, the supernova limits put the electron-neutrino mass at less than 16 eV. The square of the electron mass is about 250 GeV^2. The solution of the seesaw equation then requires that the unknown mass scale be greater than 16 GeV. When the calculation is run for the 1.8-GeV tau mass and the 65-eV cosmological upper limit on the tau-neutrino mass, one finds a more stringent lower limit of 5×10^7 GeV.

One sees that by the seesaw mechanism the incredibly tiny neutrino mass is the consequence of a mass scale much greater than what is attainable by present colliding-beam accelerators. If the mechanism is correct, these mass scales should be associated with new particles—perhaps a fourth quark or lepton. The seesaw mechanism would then have cosmological implications as well: it raises the possibility that the fourth neutrino might provide the so-called missing mass needed to close the universe.

Current theoretical prejudice requires that the mass density of the universe be just sufficient to eventually halt the present expansion and cause the universe to recollapse, in which case the universe is said to be "closed." The available evidence, however, indicates that the observed mass density of the universe is only between 10 and 20 percent of this critical value. Astronomers are therefore now engaged in an extensive search for the "missing mass."

A neutrino that provides the missing mass cannot be too massive. Neutrinos are even more plentiful than photons—several billion for every proton, electron and neutron—and if any one type of neutrino had a mass equal to the 65-eV value, that would be enough by itself to close the universe. If the neutrino mass were much above this value, the resulting gravitational pull would be sufficient to slow the observed expansion rate of the universe noticeably. The fact that no such effect is observed has led most physicists to accept 65 eV as an upper limit.

Now, it is known from experiment that any fourth charged lepton must have a mass greater than 41 GeV. Given this number for the charged lepton's mass and 65 eV for the fourth neutrino's mass, the seesaw mechanism yields a value of 2.5×10^{10} GeV for the unknown mass scale. Assuming that this single mass scale generates the masses of all the neutrinos, one then computes by the seesaw mechanism that the neutrino masses must be less than 10^{-8} eV, 4×10^{-4} eV and .1 eV respectively for the electron neutrino, mu neutrino and tau neutrino. If this argument is correct, the fourth neutrino could provide the missing mass, but the three neutrinos already known would be much too light to have any effect.

Experiments Under Way

Such arguments for the existence of a fourth family of quarks and leptons are admittedly speculative. Yet some direct searches are under way. One technique was first suggested by the author and Carlo Rubbia of CERN. It uses the decay of the *W* particles to discover, or to put a limit on, the mass of a possible fourth charged lepton. Recent experiments at CERN give a 41-GeV limit. Notice that this is between one order and two orders of magnitude more massive than the tauon, which is what one would expect from the mass hierarchy discussed above. If the mass of the next quark or charged lepton is less than 70 GeV, present-day machines may be able to detect them in the near future. Otherwise physicists will have to wait for the Superconducting Supercollider or for the Large Hadron Collider that has been proposed at CERN.

One might well wonder whether, if a fourth family of quarks and leptons is uncovered, a fifth will be far behind. This question is being addressed by both cosmologists and particle physicists in ongoing attempts to count neutrino families.

From the cosmological standpoint, the number of neutrino families has a profound effect on the production of light isotopes in the process of primordial nucleosynthesis that occurred in the first few minutes after the big bang. The final abundances of these isotopes, in particular helium and deuterium, depend on how fast the universe was expanding in relation to the rate of the isotope-producing nuclear reactions. The expansion rate of the universe in turn depends on the number of particle species in existence, including families of neutrinos. The more neutrino families there are, the faster the universe expands and the more helium is produced. Comparing the helium produced by nucleosynthesis calculations with observational upper limits then constrains the number of possible neutrino families [*see box on opposite page*]. Remarkably, such considerations limit the number of neutrino families to four, or conceivably five. Assuming that the quark-lepton pairing of the standard model continues to higher families, this then limits the number of quark families to four or five too.

Such cosmological limits on particle species have traditionally been taken with large grains of salt by particle physicists. Now, however, laboratory experiments are coming to the same conclusion. These experiments utilize the Z^0 particle, which is able to decay into all existing neutrino families. The more neutrino families there are, the faster the Z^0 is able to decay. Hence, by measuring the Z^0 lifetime, physicists can determine the number of neutrino families existing in nature. Preliminary results from SLAC, CERN and DESY have already limited the number of neutrino families to five. Refinements will eventually give an exact number—not just an upper limit: direct evidence for or against a fourth family of quarks and leptons.

If a family beyond truth and beauty is established, physicists will no doubt ask: Why four? Why are the fourth-family masses so large? Why is four (an even number) also the number of dimensions of spacetime? Is this the result of superstring theory, which specifies the number of possible dimensions? Admittedly, questions that ask why lead to infinite regress. Yet the only thing science can do is to reduce many problems to a few. If the introduction of the fourth family of quarks and leptons explains the mass distribution of the first three families, transition probabilities, missing mass and the nature of charge-parity violation—then it will have accomplished a great deal.

FURTHER READING

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