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The Leptons After 100 Years

Puzzles and mysteries abound: Are there more than just the six leptons already known; what is the intrinsic difference between the electron, the muon and the tau; do neutrinos have mass?

Martin L. Perl

Over the course of a century, six leptons have been discovered in the universe of elementary particles. Three—the electron, muon and tau—each have one unit of electric charge; the other three—the neutrinos—have no charge.

Borrowing from Charles Dickens, it can be said of the leptons that they are the best of particles, they are the worst of particles.

The leptons are the best of the elementary particles because, being free of the complicated strong force, they can be isolated (figure 1), allowing many of their properties to be measured directly. Also, being free of the strong force, they provide simple probes into atomic, nuclear and particle physics.

But the leptons are also the worst of the elementary particles, for we do not know if their external simplicity hides important and intricate secrets. For example, after many careful and clever experiments, we still do not know the masses of any of the neutral leptons, the neutrinos. We do not even know if the neutrino masses are zero or not zero.

The elementary particles in general are the smallest pieces of matter that we have been able to find. They are less than 10^{-16} meters in extent and perhaps have no detectable size.[1] All the known elementary particles fall into two very general types. One type, consisting of the leptons and the quarks, is made up of spin-½ particles that obey Fermi–Dirac statistics and hence are called fermions. The other type consists of the bosons, which have integral spin such as 0 or 1 and obey Bose–Einstein statistics. The bosons are force-carrying particles. For example, the gluon, spin 0, carries the strong force, and the photon, spin 1, carries the electromagnetic force.

I begin this review with one of the good aspects of the leptons, the simplicity with which they can be defined. There are four known basic forces: electromagnetic, weak, gravitational and strong.[1] The leptons are acted upon by the electromagnetic and weak forces in a well-understood way described by electroweak theory. (See table 1 on page 36.) We usually assume that the leptons are acted upon by the gravitational force, as has been demonstrated for the electron, but not for the muon or tau. And although we have no experimental evidence for the action of gravity on the neutrinos, many models for the evolution and structure of the universe assume both nonzero mass and conventional gravitational interaction for neutrinos. Notice that I have written "assume": Even defining the leptons entails assuming an answer to some of their secrets.

Leptons do not interact through the strong force, and this property decisively separates them from quarks. The strong force between quarks compels them to be buried in complicated particles such as protons and π mesons; the proton contains three quarks, the π meson contains one quark and one antiquark. We have never succeeded in making or finding a single quark isolated by itself. Conversely, leptons, free of the strong force, can be isolated and studied individually.

In thinking about defining the leptons, it is useful to remember that they are not force-carrying particles. This property separates them not only from the gluon and the photon, but also from the W and Z particles that carry the weak force, and from the theorized graviton that is supposed to carry the gravitational force.

Lepton flavor conservation and neutrinos

The three charged leptons are distinguished from each other not only by their very different masses (table 2 on page 39), but also by a mysterious, at least to me, property called lepton flavor. A student first learning about the charged leptons would reasonably expect that the heavier muon and tau would decay through the electromagnetic interaction:

$$\begin{aligned} \mu^\pm &\to e^\pm + \gamma \\ \tau^\pm &\to e^\pm + \gamma \\ \tau^\pm &\to \mu^\pm + \gamma, \end{aligned} \tag{1}$$

where γ is a photon. Why not? The mass differences provide plenty of energy for the decay, the charge is balanced and angular momentum can be balanced because the leptons have spin ½ and the photon has spin 1. But none of these decays has ever been seen!

The measured upper limit on the probability of the $\mu \to e\gamma$ decay is less than 10^{-10} compared to the observed decay of the μ (equation 2 below). The analogous upper limit for the probability of the τ decays in equation 1 is 10^{-5}.

The nonobservation of the decays in equation 1 is explained by a rule that assigns a different type or flavor to each of the charged leptons and then states that, in a reaction involving leptons, it is either very difficult or even impossible for the lepton flavor to change. Briefly, the rule says that lepton flavor is conserved. But we have no understanding of the nature of lepton flavor or of how strictly it is conserved. Indeed it was wrong for me to use the word "explained" in the first sentence of this paragraph; what we have here is a codifying of observations, not an explanation.

In spite of lepton flavor conservation, the muon and tau do manage to decay with lifetimes of 2×10^{-6} seconds and 3×10^{-13} seconds, respectively. They decay through the weak interaction, with neutrinos preserving the lepton flavor conservation. Consider the negative muon. Its principal decay mode is

$$\mu^- \to e^- + \nu_1 + \overline{\nu_2},$$

where ν_1 is a neutrino and $\overline{\nu_2}$ is an antineutrino. Specifically, the ν_1 is given the same flavor as the μ^- and is

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FIGURE 1. LIGHTNING, the most dramatic display of leptons. Unlike quarks, which are subject to the strong force, leptons are easily separated from other particles, as happens here naturally. Their isolatability makes their properties relatively easy to study. (Photograph by Ian Symonds.)

denoted ν_μ for muon neutrino. Thus, muon flavor is conserved by being transferred from the μ^- to the ν_μ. And the creation of the e^- is compensated by the creation of an antielectron neutrino $\overline{\nu_e}$ with antielectron flavor. Thus, the decay is

$$\mu^- \rightarrow e^- + \nu_\mu + \overline{\nu_e}. \qquad (2)$$

Similarly, the τ^- decays about 20% of the time through each of the analogous processes

$$\tau^- \rightarrow e^- + \nu_\tau + \overline{\nu_e}$$

$$\tau^- \rightarrow \mu^- + \nu_\tau + \overline{\nu_\mu}.$$

The remaining 60% of the time, the τ^- decays into a tau neutrino, ν_τ, and hadrons. Hadrons have zero lepton flavor. Examples are

$$\tau^- \rightarrow \nu_\tau + \pi^-$$

$$\tau^- \rightarrow \nu_\tau + \pi^- + \pi^- + \pi^+.$$

There are other observed and nonobserved interactions of the charged leptons that fit together with the nonobservation of the decays in equation 1. For example, the reactions

$$e^+ + e^- \rightarrow \mu^+ + \mu^-$$

$$e^+ + e^- \rightarrow \tau^+ + \tau^-$$

are well known, and the second one is the way in which we produce tau's to study their properties. But reactions such as

$$e^+ + e^- \rightarrow \mu^+ + e^-$$

$$e^+ + e^- \rightarrow \tau^+ + \mu^-$$

have never been observed.

Thus, each of the three known neutrinos is associated with a specific charged lepton (summarized in table 2). This association dominates the interaction of the leptons with hadrons. At high energies, when a ν_μ collides with a proton p, we observe

$$\nu_\mu + \mathrm{p} \rightarrow \nu_\mu + \text{hadrons}$$

and

$$\nu_\mu + \mathrm{p} \rightarrow \mu^- + \text{hadrons}.$$

But we have never observed

$$\nu_\mu + \mathrm{p} \rightarrow \nu_e + \text{hadrons}$$

or

$$\nu_\mu + \mathrm{p} \rightarrow e^- + \text{hadrons}.$$

Neutrino masses and frustration

The masses of the charged leptons are well known (table 2), although we have absolutely no understanding of why the μ mass is about 200 times the e mass and the τ mass is about 17 times the μ mass. We have measured only upper limits for the neutrino masses (figure 2 and table 2). Therefore, at present the neutrinos are distinguished from each other only by their associated charged lepton. The upper limits come from the limited precision of the technology of the experiments used to measure the neutrino mass. (See box 1 on page 36.) Unfortunately, in all three cases the limited measurement precision of the energy and momentum of the particles, combined with other experimental problems, has defeated the experimenter. It is very frustrating.

Individuals outside elementary particle physics may justifiably wonder at our concern about neutrino masses. So what if the neutrinos have masses much smaller than their associated charged leptons? Most particle physicists see two problems. First, suppose the neutrinos have zero mass like the photon. The photon's zero mass is related to a basic invariance property of the electromagnetic field.

Similarly a zero mass for the neutrinos should signify something basic—but what? The second problem occurs if the neutrinos have nonzero mass. We already know that the ratio of the ν_e mass to the e mass is less than 3×10^{-5}; what is the significance of such a small number? In quark pairs the smallest mass ratio is that of the bottom quark mass to the top quark mass, about 3×10^{-2}.

I find that most workers in elementary particle physics believe that the neutrinos have nonzero mass. But I think some of this belief is emotional: There would seem to be nothing more to learn about the neutrinos if they had no mass, unless a new Einstein is stimulated by the simplicity of zero to find a new general principle in particle physics. I am a bit skeptical about the hope for nonzero neutrino mass; nature would have to be particularly cruel to have set all the neutrino masses below the reach of present experimental precision. But then, nature has been cruel to physicists in the past.

A little later in this article I discuss an indirect way in which nonzero neutrino masses might be found; it is a more delicate way, a way that depends on lepton flavor nonconservation between neutrinos.

Table 1. Definition of leptons and the differences between leptons and quarks

Property	Lepton	Quark
Acted upon by the electromagnetic force?	Yes	Yes
Electric charge in units of 1.6×10^{-19} coulombs	+1, −1 or 0	+2/3, −2/3, +1/3 or −1/3
Acted upon by the weak force?	Yes for all known leptons	Yes
Acted upon by the gravitational force?	Yes for electron, assumed for other leptons	Yes for up and down quarks, assumed for other quarks
Acted upon by the strong force?	No	Yes
Can be isolated as a single particle?	Yes	Never observed, therefore taken as no

Are there more leptons?

Since the discovery of the tau and the deduction of the discovery of the tau neutrino 20 years ago (see PHYSICS TODAY, December 1995, page 17), there have been many, many searches for additional leptons. Yet no more have been found. I am as surprised as anyone. When my colleagues and I in the 1960s started thinking about looking for charged leptons more massive than the muon, I was motivated by my sequential lepton model.[3] I thought there was a long series of charged leptons and associated neutrinos, with each neutrino being much less massive than its charged lepton:

$$\begin{array}{cc} e & \nu_e \\ \mu & \nu_\mu \\ \mathrm{L} & \nu_\mathrm{L} \\ \mathrm{L'} & \nu_{\mathrm{L'}} \\ \cdot & \cdot \\ \cdot & \cdot \\ \cdot & \cdot \end{array}$$

When we discovered the tau in the 1970s, this model seemed even more reasonable.

Since then, the powerful method used to discover the tau at the electron–positron circular collider called SPEAR,

$$e^+ + e^- \rightarrow \tau^+ + \tau^-,$$

has been used at ever-increasing energies to search for the next charged lepton. In the reactions

$$e^+ + e^- \rightarrow \text{virtual } \mathbf{photon} \rightarrow \mathrm{L}^+ + \mathrm{L}^-$$
$$e^+ + e^- \rightarrow \text{virtual } \mathrm{Z}^0 \text{ or real } \mathrm{Z}^0 \rightarrow \mathrm{L}^+ + \mathrm{L}^-,$$

when the e^+ and e^- have the same energy E and collide

Box 1: Measuring Neutrino Masses Directly

The upper limit on the ν_μ mass comes from the decay

$$\pi^+ \rightarrow \mu^+ + \nu_\mu.$$

If the π^+ decays at rest, the μ^+ and ν_μ are produced with equal and opposite momentum p. From energy conservation,

$$\sqrt{p^2c^2 + m(\mu)^2c^4} + \sqrt{p^2c^2 + m(\nu_\mu)^2c^4} = m(\pi)c^2.$$

From this and our knowledge of $m(\mu)$ and $m(\pi)$ and the measurement of the muon's momentum, the mass of the ν_μ can be found. But at present there is not enough precision in these masses and momentum measurements, and experimenters are left with an upper limit on $m(\nu_\mu)$ of 0.17 MeV/c^2.

The upper limit of about 20 MeV/c^2 for the ν_τ mass comes from a more complicated measurement, being derived from studies of τ decays such as

$$\tau^- \rightarrow \nu_\tau + \pi^- + \pi^- + \pi^- + \pi^+ + \pi^+.$$

Consider the set of these decays in which the total energy of the five pions, $E_{5\pi}$, uses up just about all the mass energy, $m(\tau)c^2$, of the τ. Then the upper bound on the ν_τ mass is given by

$$m(\nu_\tau)c^2 \leq m(\tau)c^2 - E_{5\pi}.$$

Suppose that, after measurement of many 5π decays, we find that $E_{5\pi}$ never exceeds a maximum value $E_5\pi(\max)$; then the ν_τ mass is given by

$$m(\nu_\tau)c^2 = m(\tau)c^2 - E_{5\pi}(\max).$$

Similarly, the upper limit on the ν_e mass comes from studying the e^- energy spectrum in the decay of tritium to helium-3:

$$^3\mathrm{H} \rightarrow {}^3\mathrm{He} + e^- + \overline{\nu_e}.$$

The ν_e mass has been probed down to masses of less than 10 eV/c^2. But atomic and molecular physics effects at the several eV/c^2 levels complicate the measurement, and it is safer to give an upper limit of 15 eV/c^2. The e^- energy spectrum also has an unexplained shape that confuses the measurement.

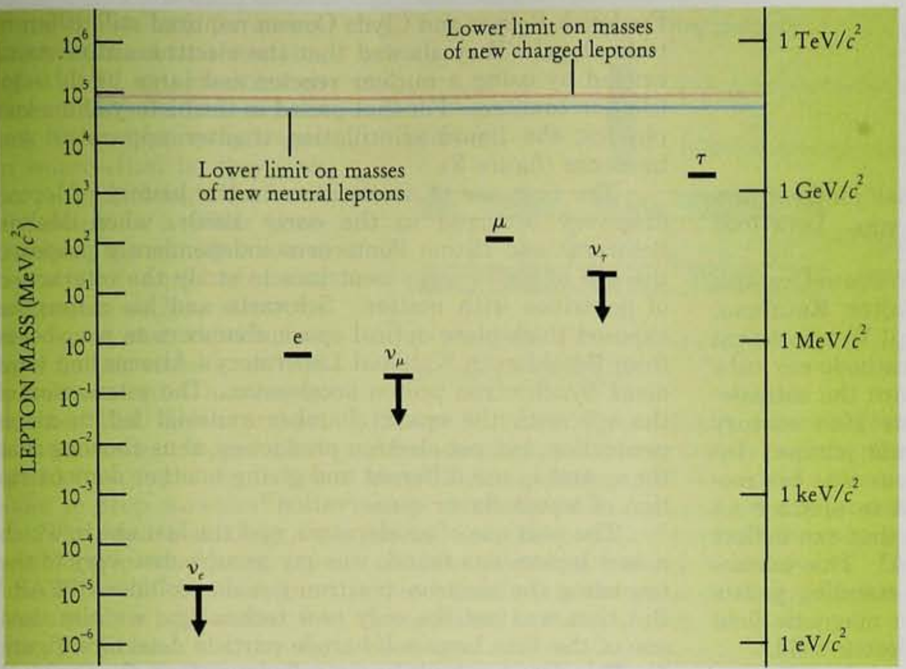

FIGURE 2. LEPTON MASSES. This logarithmic plot shows the masses of the charged leptons and upper limits on the masses of the neutrinos. There is no lower limit from experiment on the neutrino masses—indeed, they might be zero. The mass unit MeV/c^2 is equivalent to 1.8×10^{-30} kg.

head on, the search can be made up to a lepton mass $m(\mathrm{L}) = E/c^2$. As I write this article, the LEP 2 electron–positron collider at CERN has been used to search up to E of about 80 GeV. But no additional charged lepton has been found. This means that if L exists, $m(\mathrm{L}) > 45\ m(\tau)$, a larger ratio gap than exists between the τ and the μ.

Searches for neutral leptons are more difficult, because the reaction

$$e^+ + e^- \rightarrow \text{virtual } Z^0 \rightarrow \nu_\mathrm{L} + \overline{\nu_\mathrm{L}}$$

cannot be detected directly. However, it can be detected indirectly when the reaction is carried out through a real Z^0,

$$e^+ + e^- \rightarrow \text{real } Z^0 \rightarrow \nu_\mathrm{L} + \overline{\nu_\mathrm{L}},$$

because this reaction broadens the decay width of the Z^0. Of course, $m(\nu_\mathrm{L})$ must be less than $m(Z^0)/2$. Because $m(Z^0)$—the mass of the Z^0—is about 91 GeV/c^2, there are no additional neutrinos with a mass of less than about 45 GeV/c^2.

These lower bounds for $m(\mathrm{L})$ of about 80 GeV/c^2 and for $m(\nu_\mathrm{L})$ of about 45 GeV/c^2 apply not only to leptons that follow the sequential lepton model, but also to hypothetical leptons with different properties. For example, we can consider a charged lepton L that has no associated neutrino, or a charged lepton L whose associated neutrino is more massive: $m(\nu_\mathrm{L}) > m(\mathrm{L})$. If the lepton number of L is conserved, it will be stable; if it is not conserved, then L could decay to one or more of the known leptons. Searches for these sorts of leptons have also been fruitless up to a mass of about 80 GeV/c^2.

Similarly, there have been speculations about a massive stable neutrino N not associated with any charged lepton; or N might be stable because it is associated with a more massive charged neutrino; or the decay of N might violate lepton conservation. Once again, nothing has been found, and the lower limit on $m(\mathrm{N})$ is 45 to 80 GeV/c^2, depending on the model used in the speculation.

We can go further in speculation. We would still call a particle a lepton if it were acted on only by the electromagnetic interaction—that is, if it avoided the weak force as well as the strong force. Such a particle would play havoc with the beautiful unified theory of the weak and electromagnetic interaction, but no such lepton has been found and there is no need to worry at present.

The search for new leptons has expanded in yet other directions. For example, the known leptons all have spin ½. Could there be leptons with spin 0 or 1? Certainly we can maintain the lepton definition as long as the particle avoids the strong interaction but is acted upon by the weak and electromagnetic forces. Indeed, the popular hypothesis in particle physics called supersymmetry predicts that every known lepton has a partner with spin 0. Thus, the partner of the spin-½ electron is called a slepton and has spin 0 but still has the electron charge $\pm q$. Supersymmetric theory does not require that the particle partners have the same masses; and no supersymmetric partners have been found. The lower limits on the masses once again are 45 to 80 GeV/c^2, depending on the details of the supposed decay process of the supersymmetric particle.

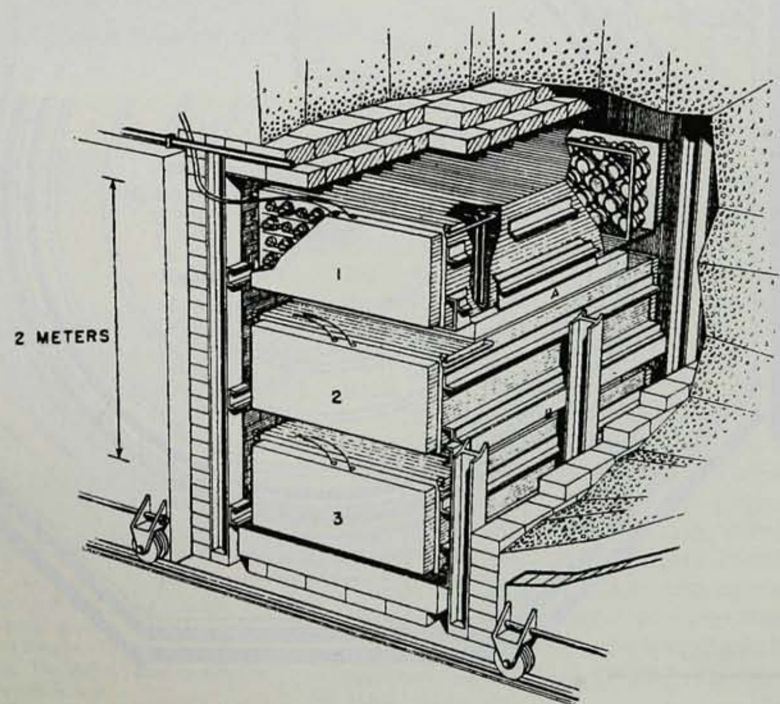

FIGURE 3. LIQUID SCINTILLATOR APPARATUS used by Frederick Reines and Clyde Cowan to detect the electron antineutrino. (From ref. 7, 1960.)

Technology and lepton discovery

The reactions

$$e^+ + e^- \rightarrow L^+ + L^-$$
$$e^+ + e^- \rightarrow \nu_L + \overline{\nu_L}$$

may not be the best way to search for some kinds of new leptons; they are certainly not the only way. Let's look back at the history of lepton discovery.

In the late 19th century research of William Crookes, Eugen Goldsmith, Heinrich Hertz, Walter Kaufman, Philipp Lenard, Joseph Thomson and Emil Weichert that led to the discovery of the electron, the cathode-ray tube was the primary apparatus.[4] Working with the cathode-ray tube required understanding the late 19th century technologies of gas discharges and vacuum pumps. Indeed, one of Thomson's major contributions was his recognition that a good vacuum is required to produce an electrostatic field inside the tube, a field that can deflect the electrons making up the cathode ray.[5] This accomplishment of Thomson resolved the long-standing puzzle of why a cathode ray was deflected in a magnetic field but appeared not to be deflected in an electric field.

The muon was discovered in cosmic rays by following the mystery of penetrating radiation—particles that pass through the atmosphere with little interaction compared to the interactions expected from electrons or protons. The penetrating radiation puzzle began in the 1920s. But it was not until the 1930s and early 1940s that the new technologies of triggered cloud chambers and coincidence circuits finally led to the identification of the muon and its separation from the pion.[6]

The discovery of the electron antineutrino by Frederick Reines and Clyde Cowan required still different technology.[7] They showed that the electron antineutrino existed by using a nuclear reactor and large liquid scintillation counters. For that period in the history of nuclear physics, the liquid scintillation counter apparatus was immense (figure 3).

The first use of accelerators in the history of lepton discovery occurred in the early 1960s, when Melvin Schwartz and Bruno Pontecorvo independently proposed the use of high-energy neutrinos to study the interaction of neutrinos with matter. Schwartz and his colleagues exposed thick-plate optical spark chambers to a ν_μ beam from Brookhaven National Laboratory's Alternating Gradient Synchrotron proton accelerator. The interaction of the ν_μ's with the spark chamber material led to muon production, but not electron production, thus showing that the ν_e and ν_μ are different and giving another demonstration of lepton flavor conservation.[8]

The next use of accelerators, and the last use in which a new lepton was found, was my group's discovery of the tau using the electron–positron circular collider SPEAR.[9] But that was not the only new technology; we also used one of the first large-solid-angle particle detectors (figure 4). This detector, built by my colleagues from the Stanford Linear Accelerator Center and Lawrence Berkeley National Laboratory, consisted of a central magnetostrictive wire spark chamber surrounded by sandwiches of plastic scintillation counters and lead plates, these sandwiches allowing us to detect photons and identify electrons. Then came the coil producing an axial magnetic field, and outermost layers of iron and spark chambers for muon identification.

And so each lepton was discovered using a different experimental technology. Perhaps this was simply because the discoveries stretched over 80 years. Or perhaps leptons are so elusive that a new technology is required for each discovery. Perhaps the next charged lepton, call it λ, is so massive that it is beyond the energy reach of present or near-future $e^+ + e^- \rightarrow L^+ + L^-$ search technology. The mass need only be above several 1000 GeV/c^2 to be out of reach.

There are two methods, using different technologies, that could lead to the discovery of the λ if—and this is a crucial if—the λ already exists in matter. Thus, the λ would have been created in the early universe and would have to be sufficiently stable to still exist.

One of the technologies involves using mass spec-

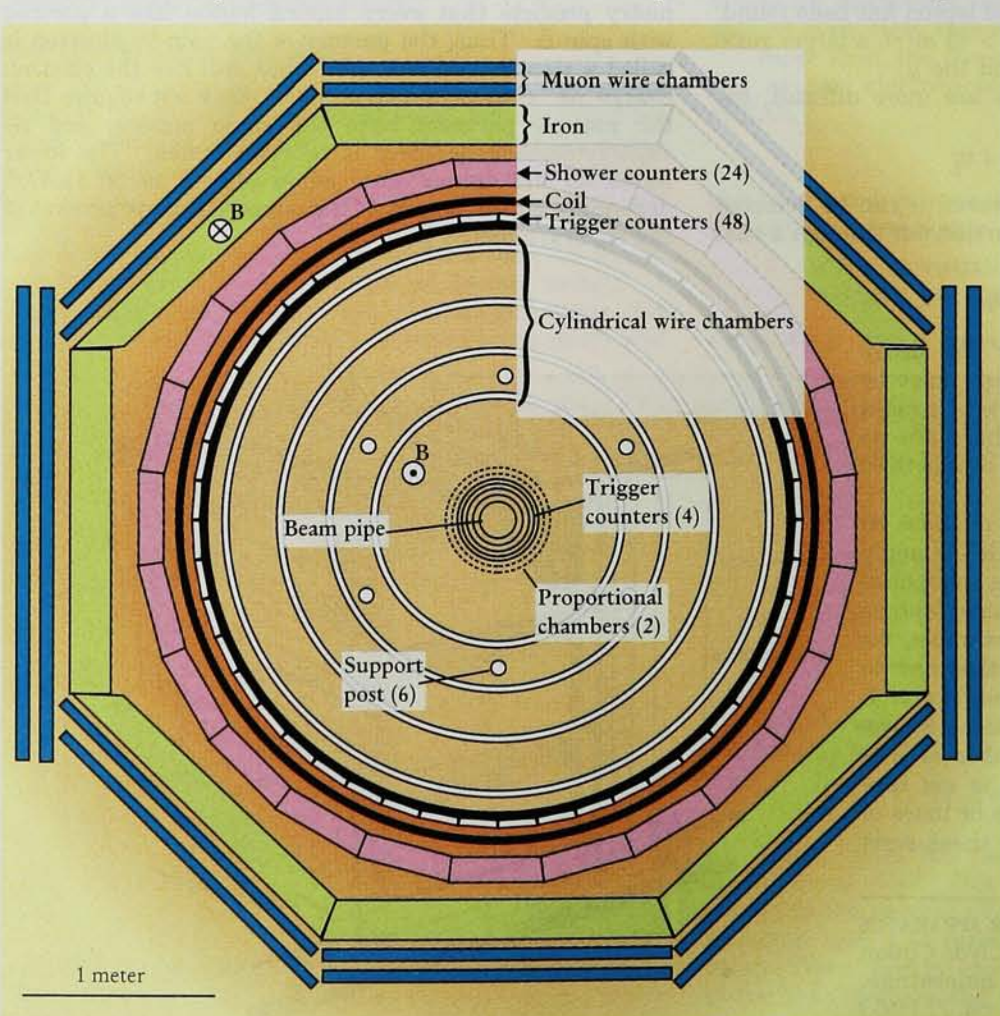

FIGURE 4. TAU DETECTION apparatus. This large-solid-angle detector, built by a team from the Stanford Linear Accelerator Center and Lawrence Berkeley National Laboratory, played a key role in the discovery of the tau.

trometry[10] to look for a very heavy nucleus that contains the λ^+. In a typical search experiment, the researchers look for very heavy hydrogen in water—that is, they look for λ_2O. Although the basic apparatus is a mass spectrometer, the sample is sometimes first enriched using techniques such as electrolysis. So far, such experiments have had no success. A 1993 search covered λ masses up to about 1500 GeV/c^2 and set a concentration upper limit of 10^{-16} λ's per hydrogen atom in deep seawater.[11]

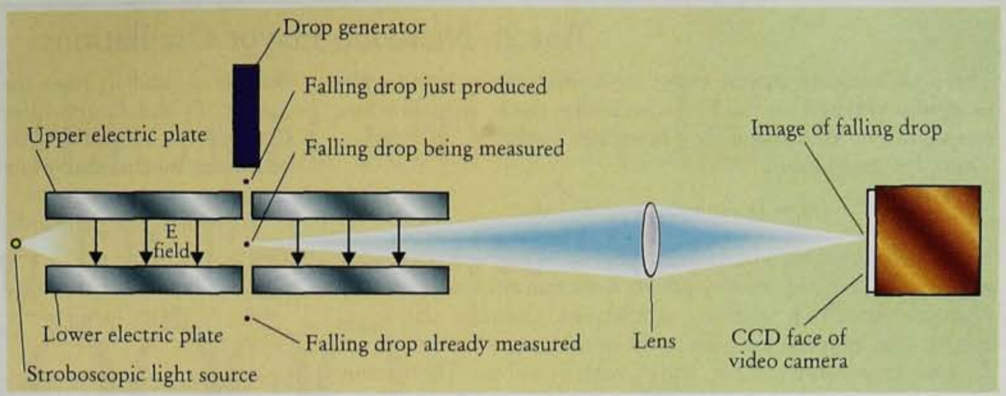

FIGURE 5. FRACTIONAL CHARGE detection scheme, showing apparatus being used to search for massive leptons or other massive particles possessing fractional electric charge. Small liquid drops, 7 μm in diameter, fall through air. The air resistance and the small drop size cause the drops to rapidly attain a terminal velocity proportional to the force on the drop. A vertical electric field that periodically changes direction makes it possible to measure two terminal velocities, one for each electric field direction. The difference of the two terminal velocities is proportional to the charge on the drop. The sum of the two terminal velocities is proportional to the drop mass.

The other technology for searching for very heavy leptons is part of the more general search in bulk matter for *free* particles, not bound quarks, with fractional electric charge.[12] Such a particle might have a charge of 0.1 q or 2/3 q or πq, where q is the magnitude of the electron charge. My colleagues and I have been carrying out a general search for particles with fractional electric charge using a highly automated version of the Millikan oil drop experiment.[13] (See figure 5.) What does this have to do with leptons? Well, why couldn't the next lepton have fractional electric charge? Such a lepton could have been produced in the early universe and would probably be stable. Past searches in bulk matter for free particles with fractional electric charge show that such particles are rarer than one for every 10^{20} nucleons; but the chemical processes used to produce the samples have raised questions as to the strictness of this limit.

Do neutrinos change their lepton flavors?

There has been some evidence and a great deal of theory and speculation that neutrinos may not obey perfect lepton flavor conservation.[14] The broadest evidence comes from measurements of the electron neutrino flux reaching Earth from the Sun. In the nuclear fusion reactions that power the Sun, ν_e's are produced in a variety of ways. For example, there are the pp fusion reaction

$$p + p \rightarrow {}^2H + e^+ + \nu_e + 0.42 \text{ MeV}$$

and the boron decay

$${}^8B \rightarrow {}^8Be + e^+ + \nu_e + 14.6 \text{ MeV}.$$

The ν_e's that reach Earth are detected using weak-interaction reactions of the ν_e. But only about two-thirds of the expected ν_e flux is observed, the expected flux having been calculated from models of the Sun's properties and energy production. The hypothesis is that in the course of traveling from the energy-producing inner core of the Sun to Earth, some ν_e's have changed into the other neutrinos, ν_μ or ν_τ. These ν_μ's or ν_τ's would not have enough energy to produce μ's or τ's, nor would they participate in the reactions used to detect the expected ν_e's.

The general hypothesis is that the change from, say, ν_e to ν_μ would not be permanent, but would be part of an oscillation between ν_e and ν_μ. The oscillation would depend on a mixing angle, θ, and an oscillation rate. And the oscillation rate would depend upon the *masses* of the neutrinos! Thus, if neutrinos oscillated between lepton flavor, not only would this be a wonderful new phenomenon in elementary particle physics, but in addition neutrino masses could be indirectly measured. (See box 2 on page 40.)

This section is headed with a question because the case is not yet proven. The most important open question is whether the calculations of the Sun's properties and the predicted ν_e flux are correct.[15] There are also open questions about the consistency of the various measurements of the ν_e flux. Powerful new experiments will certainly clarify the experimental consistency issues (see PHYSICS TODAY, July 1996, page 30).

Table 2. Properties of the charged leptons and their associated neutrinos

Generation	1	2	3
Charged lepton name	Electron	Muon	Tau
Charged lepton symbol	e	μ	τ
Charged lepton mass in units of MeV/c^2	0.51	106	1777
Charged lepton lifetime in seconds	Stable	2.2×10^{-6}	2.9×10^{-13}
Associated neutrino symbol	ν_e	ν_μ	ν_τ
Upper limit on neutrino mass in MeV/c^2	about 1.5×10^{-5}	0.17	about 20

The magnitude of electric charge of the charged leptons is 1.6×10^{-19} coloumbs, the particles being arbitrarily defined to have negative charge and the antiparticles to have positive charge. The neutrinos, of course, have zero electric charge. The generation number 1, 2, 3 gives the historical order of discovery of the charged leptons; that is also the order of the masses of the charged leptons. The first generation in no known way is more fundamental than the second or third generation. The MeV/c^2 mass unit equals 1.78×10^{-30} kg. For additional information on lepton properties, see reference 2.

Box 2: Neutrino Flavor Oscillations

The possibility of lepton flavor nonconservation among the neutrinos is based on the hypothesis that the ν_e, ν_μ and ν_τ are combinations of three other neutrinos called ν_1, ν_2 and ν_3. Then, for example,

$$\nu_\tau = U_{\tau 1}\nu_1 + U_{\tau 2}\,\nu_2 + U_{\tau 3}\,\nu_3.$$

It is assumed that each of the neutrinos ν_1, ν_2 and ν_3 has a unique mass, so that ν_e, ν_μ and ν_τ are each mixtures of masses. To illustrate how this leads to oscillations, consider the ν_μ–ν_τ system and suppose that the only nonzero coefficients U are U_{e1} and those connecting ν_μ and ν_τ with ν_2 and ν_3. Then, using the mixing angle θ and setting $U_{\mu 2} = \cos\theta$,

$$\nu_e = U_{e1}\,\nu_1$$

$$\nu_\mu = \nu_2 \cos\theta + \nu_3 \sin\theta$$

$$\nu_t = -\nu_2 \sin\theta + \nu_3 \cos\theta.$$

There are several ongoing and planned high-energy experiments that begin with a ν_μ beam entering the apparatus. As the ν_μ moves downstream with momentum p, its time evolution is given by

$$\nu_\mu(t) = \nu_2 \cos\theta \exp(-iE_2t/\hbar) + \nu_3 \sin\theta \exp(-iE_3t/\hbar).$$

Because ν_2 and ν_3 have the same momentum p but different masses, E_2 and E_3 are different. Therefore, with time, ν_2 and ν_3 move out of phase with each other. This is a well-known quantum mechanical phenomenon, and it means that $\nu_\mu(t)$ acquires a ν_τ component!

At time t, the probability of the ν_μ having oscillated into a ν_τ is

$$\mathrm{P}(\nu_\mu \to \nu_\tau) = \frac{\sin^2 2\theta}{2}\left(1 - \cos\frac{E_2 - E_3}{\hbar}\,t\right).$$

In the approximation that p is much larger than mc,

$$E_2 - E_3 = (m_2{}^2 - m_3{}^2)\,c^3/2p.$$

Thus, the second term in this equation gives an oscillation between ν_μ and ν_τ, and the oscillation frequency is proportional to the difference of the squared masses, $m_2{}^2 - m_3{}^2$. Therefore, if experiments find ν_τ's in a beam that was initially all ν_μ's, we learn not only that the mixing angle θ is nonzero, but also something about the size of neutrino masses. Past experiments have not found such a signal; θ for $\nu_\mu - \nu_\tau$ mixing is less than about 3×10^{-2} for $m_2{}^2 - m_3{}^2$ greater than about 10 eV^2/c^4. This means that ν_μ is mostly ν_2 and ν_τ is mostly ν_3 if the mass-squared differences are above 10 eV^2/c^4.

What is needed is a terrestrial experiment in which neutrino oscillations are detected directly. There have been many attempts to do this. Except for one experiment, there has been no such detection of neutrino oscillations, and the results of that one experiment are yet to be confirmed. But particle physics experimenters are persistent. Experiments to detect neutrino oscillations are going on now, and more are planned.

Practical uses for the other leptons

There is no end to the practical uses of the electron. What about the other leptons? Will they ever be used in the technology of daily life or even for exotic engineering? There is no active use at present for the muon, the tau or the neutrinos, but there have been suggestions:

▷ The ability of muons to catalyze fusion was shown experimentally in 1957, and there has been substantial experimental and theoretical research on muon catalysis of fusion since then.[16] In the simplest case, a μ^- forms a molecule, pμd with a proton p and a deuteron d. The p and d are sufficiently close so that a fusion reaction occurs:

$$\mathrm{p}\mu\mathrm{d} \to {}^3\mathrm{He} + \mu^- + 5.5\ \mathrm{MeV}$$

We don't have muon catalyzed fusion reactors today, because with existing technology the energy required to produce the muons is greater than the energy from the fusion.

▷ Cosmic-ray muons were used once to look for hidden chambers in the pyramids, but no new chambers were found.[17] I have not heard of any other engineering use of the penetrating power of muons.

▷ There have been suggestions that muon neutrino beams could be used for geological research and prospecting deep in the Earth.[18] The rate of interaction of the neutrinos would be proportional to the density of matter, with the interaction rate being measured by the muons so produced. Certainly that would be a grand engineering project.

▷ As for the tau, to my knowledge, there has yet to be even one speculation as to its use.

The next hundred years

And so we enter the second hundred years of lepton research with mysteries and puzzles to solve. We are no smarter than the physicists whose work led to the discovery of the electron—Crookes, Goldsmith, Hertz, Kaufman, Lenard, Thomson, Weichert—but we are just as persistent, and there are more of us.

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