Heavy Leptons

The class of elementary particles of matter that includes the electron and the muon has a new member: the tau. It may be the first in a sequence of charged heavy leptons

by Martin L. Perl and William T. Kirk

The small family of elementary particles known as the leptons (from the Greek for "light ones") can be distinguished from the two other major classes of subatomic matter by a number of criteria, among which mass is perhaps the least important. For example, the leptons differ from the generally heavier hadrons primarily by being insensitive to the strong nuclear force, the dominant short-range force that binds together the particles of the atomic nucleus. The leptons share this immunity to the strong force with the photon, the massless carrier of the electromagnetic force, which forms a one-member class of its own. Unlike the photon, however, both the leptons and the hadrons are capable of interacting by means of the weak nuclear force, the even shorter-range force responsible for the radioactive decay of nuclear particles.

One of the most striking things about the leptons is that there are so few of them. Here again they stand in contrast to the hadrons, which have proliferated notoriously in recent years, reaching the point where they now total several hundred distinct particles, arrayed in various subclasses. The most familiar of the hadrons are the two main constituents of the atomic nucleus, the proton and the neutron; one of the latest additions to this class is the psi, or *J*, particle, discovered in 1974. (Burton Richter of Stanford University and Samuel C. C. Ting of the Massachusetts Institute of Technology shared the 1976 Nobel prize for physics for their independent discovery of this particle.) The lepton family, on the other hand, has for some time been thought to consist of only four particles (together with their corresponding antiparticles): the electron, discovered in the form of cathode rays more than 80 years ago; the muon, first observed in cosmic-ray showers some 40 years ago, and two kinds of neutrino, one associated with the electron (called the electron neutrino) and the other associated with the muon (the muon neutrino). Neutrinos, long suspected on theoretical grounds, were detected for the first time some 20 years ago.

Another sense in which the leptons are special has emerged just recently. A considerable body of evidence points to the conclusion that hadrons are not elementary particles at all but rather are composite structures built up of the simpler constituents termed quarks. Prior to the discovery of the psi particle all the known hadrons could be accounted for by assuming that they represented various combinations of three different kinds of quark (labeled "up," "down" and "strange") and their corresponding antiquarks. The main significance of the discovery of the psi particle was that it provided compelling evidence for the existence of a fourth kind of quark, which had earlier been named the "charmed" quark. According to the revised quark picture, the psi particle is a hadron consisting of a charmed quark and a charmed antiquark.

There is no evidence that the leptons are anything but pointlike objects, and so it seems that they, unlike the hadrons, are truly elementary particles, in the traditional sense of being indivisible. The list of the already known particles that can still be considered elementary in this sense has accordingly become quite short: four kinds of quarks (and their antiquarks), four kinds of leptons (and their antileptons) and the photon (which is its own antiparticle). In this context the search for additional members of the lepton family has acquired new meaning, because such particles, if any exist, would also be counted among the few genuinely fundamental constituents of matter.

During the past few years a group of physicists led by one of us (Perl) has been conducting just such a search at the Stanford Linear Accelerator Center (SLAC) as part of a larger experimental program carried out jointly by research groups from SLAC and from the University of California's Lawrence Berkeley Laboratory. We have had at our disposal a potentially powerful tool for creating new leptons: the SPEAR electron-positron storage ring, a device in which counterrotating beams of matter (electrons) and antimatter (positrons) can be made to pass through each other, causing occasional high-energy collisions in which the original particles are annihilated and, out of the resulting flash of energy, new particles are created. With this system we have uncovered evidence of the existence of a fifth kind of lepton. The new particle, which is electrically charged (like the electron and the muon), is much heavier than any of the previously known leptons; indeed, it is heavier than some hadrons. We shall relate here the story of the discovery of the new heavy lepton and its antiparticle, which we have named the tau and the antitau.

How does one go about finding a new kind of elementary particle? It helps to follow a few guiding principles. First, have a clear idea of what you are looking for; then you will know when you have found it. Second, if the object must be made artificially, as we had to do in this case, then find a way to make it in copious quantities. Third, make sure that the new object has some distinguishing characteristics that will tell you when you have it.

To get an idea of what we were looking for we took our lead from the known properties of the electron and the muon. In other words, we decided to look for a particle that has an electric charge of either -1 or $+1$ and that is acted on by both the electromagnetic force and the weak force but not by the strong force. Two questions followed. First, in our search for a new charged lepton what mass should we look for? Second, bearing in mind that the electron lasts indefinitely but that the muon decays in about two millionths of a second, what should we expect the lifetime of the new particle to be?

The question of mass was a difficult one, because there was (and still is) no theory that accounts either for the observed masses of the muon and the electron or for the ratio of their masses (approximately 200 to 1). All that was known as of four years ago was that some experiments carried out at the ADONE electron-positron colliding-

ELECTRON-POSITRON STORAGE RING at the Stanford Linear Accelerator Center (SLAC) is seen from directly overhead in this aerial photograph of the SLAC experimental area. The buildings in the photograph are arrayed in a roughly fan-shaped pattern that radiates from the high-energy end of the two-mile linear particle accelerator, located just out of the picture to the right. The SPEAR colliding-beam storage ring, which was used to create the new heavy leptons described in this article, is the oval structure near the bottom. Electrons and positrons generated by the linear accelerator are injected into the SPEAR device through the two tangential arms. The two buildings athwart the straight sections of the ring house the interaction regions, where the two counterrotating beams are made to pass through each other, causing the matter-antimatter collisions that lead to the creation of new particles. The charged-particle detector shown in the diagram on page 53 is housed in the larger of the two interaction buildings. The storage ring itself is about 80 meters across.

PARTICLE	MASS	LIFETIME	ANTIPARTICLE
ELECTRON (e^-)	.51 MeV	STABLE	POSITRON (e^+)
ELECTRON NEUTRINO (ν_e)	0	STABLE	ELECTRON ANTINEUTRINO ($\bar{\nu}_e$)
MUON (μ^-)	106 MeV	2.2×10^{-6} SECOND	ANTIMUON (μ^+)
MUON NEUTRINO (ν_μ)	0	STABLE	MUON ANTINEUTRINO ($\bar{\nu}_\mu$)
TAU (τ^-)	1,800 TO 1,900 MeV	LESS THAN 5×10^{-12} SECOND	ANTITAU (τ^+)
TAU NEUTRINO (ν_τ)	LESS THAN 600 MeV (MAY BE 0)	NOT KNOWN (MAY BE STABLE)	TAU ANTINEUTRINO ($\bar{\nu}_\tau$)

LEPTON FAMILY has until recently been thought to consist of just four weakly interacting particles (and their corresponding antiparticles): the electron, the muon and two kinds of neutrino. The mass of the newly discovered charged heavy lepton, the tau, and its antiparticle, the antitau (given here in MeV, or millions of electron volts), is approximately 4,000 times the mass of the electron and 20 times the mass of the muon. The significance of this mass ratio is not known. Muons decay abruptly into electrons through the weak interaction. Taus decay even more quickly into electrons, muons or other particles, also through the weak interaction. Not all the theoretically possible decays of the tau and the antitau have been observed.

beam facility in Italy had set a lower limit of about 1,000 million electron volts (MeV) on the mass of any new charged lepton: an energy equivalent to roughly 10 times the mass of the muon and 2,000 times the mass of the electron. Our group at SLAC, however, had no idea whether the mass of a new charged lepton, if one existed, would be within reach of our experimental equipment, which could detect particles with a mass as high as 3,500 MeV.

The question of the lifetime of the hypothetical particle, it turned out, had a better theoretical answer: less than a hundred-billionth of a second for any charged lepton with a mass greater than 1,000 MeV. The lightest charged lepton, the electron, is stable simply because there is no lighter charged particle into which it can decay. The muon is unstable because it can decay into an electron. The muon-to-electron decay does not take place in the simplest conceivable way, however, which would be for the muon to change spontaneously into an electron and a photon through the electromagnetic interaction, even though more than enough energy would be released in the process to produce a photon. Instead the muon is observed to decay through the weak interaction into three particles: an electron, an electron antineutrino and a muon neutrino.

Physicists explain this odd behavior by invoking an empirical rule whose basic significance remains unclear. They ascribe to the electron and the muon separate intrinsic properties, which we shall refer to here as "electronlikeness" and "muonlikeness," and they postulate that each of these properties is exhibited by a group of four related particles. Thus the electron, the electron neutrino, the antielectron (or positron) and the electron antineutrino are all said to exhibit the property of electronlikeness (or antielectronlikeness in the case of the antiparticles), whereas the muon, the muon neutrino, the antimuon and the muon antineutrino all exhibit muonlikeness (or antimuonlikeness). The rule then states simply that in any particle interaction or decay process involving leptons the properties of electronlikeness and muonlikeness must be separately conserved.

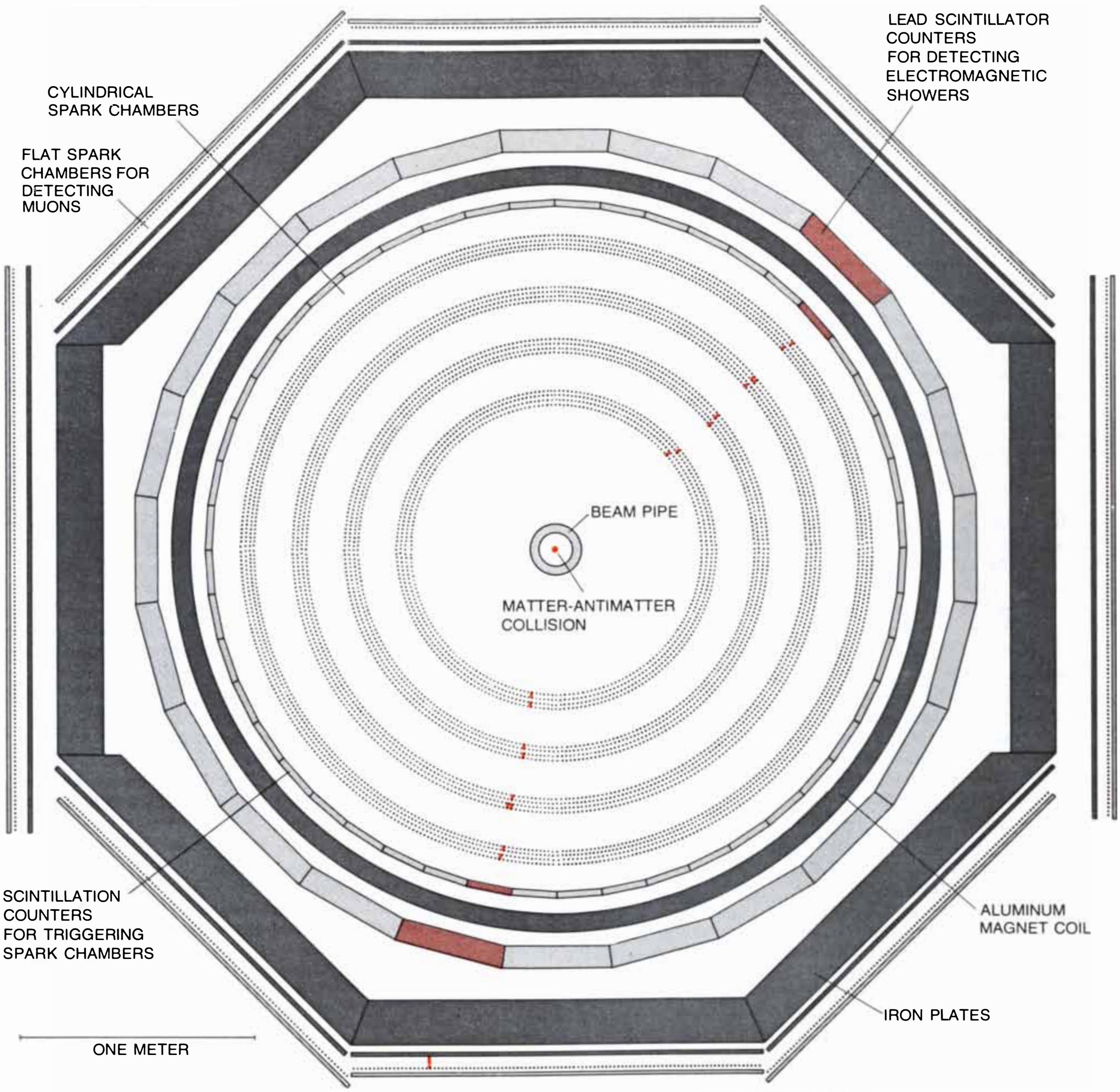
It follows that the simple electromagnetic decay of a muon into an electron and a photon is not possible because in the process the muonlikeness of the muon would have to change into the electronlikeness of the electron. The more complicated weak decay of the muon into an electron, an electron antineutrino and a muon neutrino does occur, because the muon neutrino preserves the muonlikeness of the muon, whereas the electronlikeness of the electron is exactly canceled by the antielectronlikeness of the electron antineutrino. (In actual practice particle physicists employ the terms electron lepton number and muon lepton number to denote the properties of electronlikeness and muonlikeness, and the rule in question is called the conservation of lepton number: in our view, however, these formal terms tend to obscure the fundamental mystery of the separate unique properties of the electron and the muon.)

In any event we had to decide on some comparable property for the hypothetical charged heavy lepton we were looking for. One possibility was to assign an electron lepton number (or electronlikeness) to the new lepton, thereby allowing it to decay electromagnetically into an electron and a photon. A more intriguing possibility was to assume that the new lepton-antilepton pair came with their own separate lepton number and their own associated neutrino-antineutrino pair. According to this view, the electron and the muon might be just the beginning of a sequence of charged leptons, each with its own unique "likeness." The general name adopted for these highly speculative particles at the time was sequential charged heavy leptons, with the "heavy" indicating that their masses would be greater than that of the electron or the muon. Soon after the first fragmentary evidence for such a particle was obtained, we began to use the symbol *U* (for "unknown" particle), but now that we have substantial evidence for its existence we call it tau, after the first letter of the Greek word τριτον, meaning "third." The name is meant to indicate that the tau is the third charged lepton in the sequence beginning with the electron and the muon.

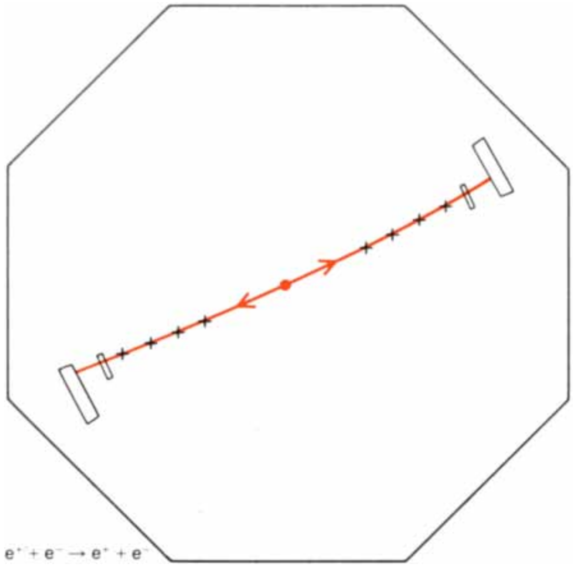
As we have noted, an effective search for a new elementary particle requires some idea of its properties, a method for producing the particle in sufficient quantities and a means of distinguishing the new particle from the particles already known. Experiments utilizing the SPEAR electron-positron storage ring at SLAC can satisfy both of the last two requirements. This machine, which began operating in 1972, consists of about 100 magnets in a ring-shaped array some 80 meters in diameter. The electron and positron beams for SPEAR, which are generated by the SLAC two-mile linear accelerator, are injected into the storage ring during a "filling time" of anywhere from 10 to 30 minutes. The beams circulate in a vacuum chamber that passes through the ring of magnets, and the deflection and focusing provided by the magnets hold the beams in stable orbits for periods of several hours. The circulating beams do not encounter each other except at two points on opposite sides of the ring, where they are made to pass through two interaction regions. In order to maximize the chance of collisions each beam contains about 100 billion particles in a single tightly packed "bunch" that is only a few centimeters long. Although each bunch makes a complete trip around the ring more than a million times a second, the chance that a particle in one beam will make a direct hit on a particle in the other beam is so remote that such a collision typically happens only once every few seconds.

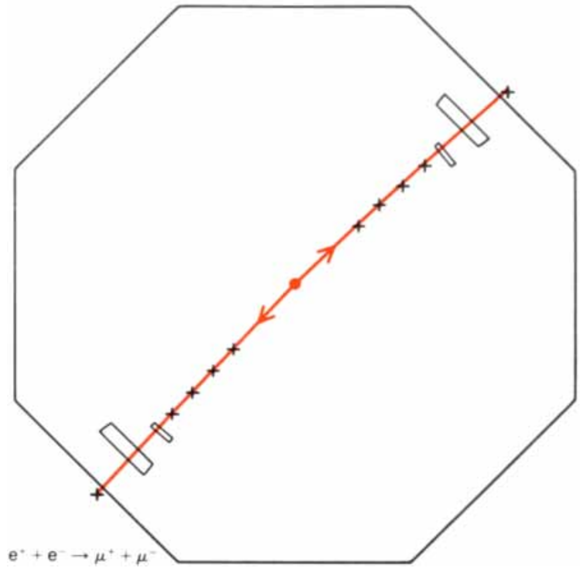
In order to study all the particles that might be produced in a single electron-positron annihilation two groups of physicists from SLAC joined forces several years ago with two groups from the Lawrence Berkeley Laboratory to build a general-purpose particle detector to surround one of the interaction regions of the SPEAR device. The detector has a cylindrical central section containing four concentric spark chambers immersed in a strong magnetic field. Surrounding the spark chambers is a system of scintillation counters for detecting charged particles. Whenever two or more charged particles are detected by the counters, the inner spark chambers are actuated and the paths of the charged particles are recorded with the aid of a computer on magnetic tape. The computer can then reconstruct the paths of the particles, yielding a diagrammatic "picture" of the event.

Outward from the scintillation counters is the aluminum magnet coil, followed by another cylindrical system of counters for detecting electromagnetic showers. These counters can distinguish electrons or positrons, which generate large showers, from hadrons or muons, which produce smaller showers. Outside all this hardware is an octagonal set of iron plates at least eight inches thick



GENERAL-PURPOSE PARTICLE DETECTOR surrounding one of the interaction regions of the SPEAR electron-positron storage ring is viewed here in cross section, with the trajectories of the colliding beams at right angles to the plane of the diagram and the collision point in the plane of the diagram at the center (*colored dot*). The cylindrical inner part of the detector contains four concentric spark chambers, each consisting of four layers of closely spaced wires (*black dots*). In the actual device there are some 100,000 such wires, strung about a millimeter apart. When the detector is in operation, a high voltage is applied across pairs of adjacent wire layers, and spark discharges (*colored dashes*) mark the ionization trails of charged particles passing through the inert gas that fills the chambers. Outside the spark chambers are two systems of charged-particle counters, separated by an aluminum magnet coil. Whenever the inner system of scintillation counters detects the passage of two or more charged particles, the cylindrical spark chambers are actuated and the paths of the particles are recorded. (The paths are bent slightly by the magnetic field; the amount of bending indicates the particle's momentum.) The outer system of lead scintillator counters registers the distinctive electromagnetic showers generated by different types of particles. Enclosing all this equipment is an octagonal set of thick iron plates. Of all the charged particles that can be produced in the electron-positron collisions at the center of the detector the only ones that can penetrate the iron and be detected in the outermost system of flat spark chambers are the muons. An interpretation of the "electron-muon" event shown in color here is given in the bottom illustration on page 55.





SIMPLIFIED DIAGRAMS of four possible outcomes of the mutual annihilation of an electron and a positron were drawn with the aid of a computer-assisted display system connected to the charged-particle detector at the Stanford colliding-beam facility. In representations of this kind electric discharges caused by the passage of charged particles through either the inner cylindrical spark chambers or the outer flat ones are symbolized by small black crosses. Only those counters that have detected particles are shown; the small rectangles are the inner "trigger" counters, and the larger, flatter rectangles are the outer electromagnetic-shower counters. The octagonal outline indicates the outer surface of the iron plates. The colored lines connecting the detection signals are bent into circular arcs by the strong magnetic field inside the magnet coil, but they are straight outside the coil. The first picture at the left shows a typical electron-positron event, in which the original electron-positron pair disappear and, out of the resulting energy, a new electron-positron pair emerge back to back, each with half of the total energy of the colliding particles. (On emerging from the collision point negatively charged particles curve right

and then more spark chambers. In general hadrons cannot penetrate the iron plates because they interact with the iron nuclei through the strong force. Electrons and positrons are also unable to penetrate the iron because they have already lost most of their energy through the production of large electromagnetic showers. Muons, however, do penetrate the iron and are detected in the outer spark chambers. Hence the detector can not only measure the direction and the momentum of the newly created particles but also separately identify hadrons, electrons and muons. It was its ability to distinguish these different kinds of particles that enabled us to find the tau-antitau pair.

The SPEAR ring can be adjusted to store beams of electrons and positrons with an energy of up to four billion electron volts (GeV) in each beam. Since the collisions that occur are between matter and antimatter, a possible outcome of such a collision is what is called an annihilation reaction. The reaction actually takes place in two steps. First the colliding electron and positron disappear, and in so doing they create the short-lived state of pure electromagnetic energy called a virtual photon. Then after an immeasurably brief time (10^{-25} second) the virtual photon rematerializes into any one of a very large number of possible combinations of new particles. Some of the possible outcomes are the re-creation of an electron-positron pair, the creation of a muon-antimuon pair, the creation of a hadron-antihadron pair (for instance a proton and an antiproton) or the creation of a large number of hadrons. What we proposed to do was to use the same method to produce a heavy lepton-antilepton pair.

If such pairs of new heavy leptons were actually being created in the electron-positron collisions at SPEAR, how would we be able to recognize them? Our earlier estimate of the tau's lifetime—less than a hundred-billionth of a second—meant that a newly created tau particle would travel less than a centimeter from its point of creation to the point where it decays, even if its velocity were roughly equal to that of light (30 billion centimeters per second). This path is too short to be directly detected by our experimental apparatus, and so we had to look for a way to recognize tau particles indirectly by identifying some distinctive pattern that appears when they decay.

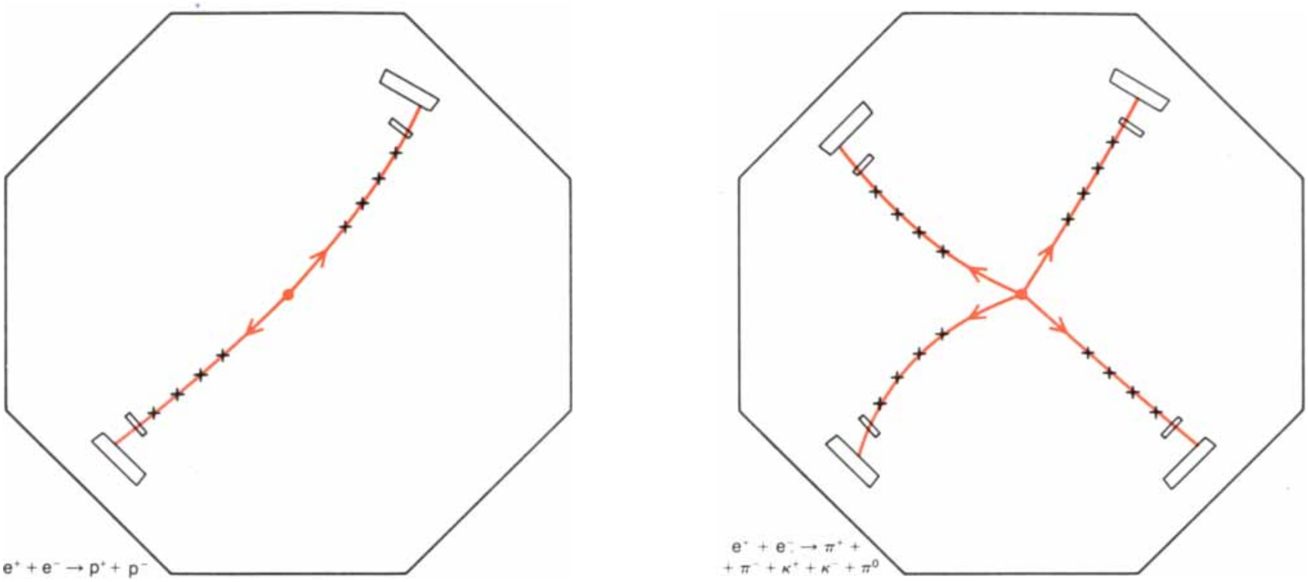
Our decision to attribute a unique lepton number, or "taulikeness," to the tau and its neutrinos meant that we did not expect the tau to decay electromagnetically into either an electron or a muon with the accompanying emission of a photon. Instead we assumed that the tau, like the muon, would decay through the weak interaction and that several different decay modes would be possible for the tau because of its large mass. We selected two of these possible weak-decay modes for special attention.

In the first decay mode the tau decays into a tau neutrino, a muon and a muon antineutrino, and in the inverse process the antitau decays into a tau antineutrino, an antimuon and a muon neutrino. In the second decay mode the tau decays into a tau neutrino, an electron and an electron antineutrino, and the antitau decays into a tau antineutrino, a positron and an electron neutrino.

These two decay modes were picked because they were expected to occur frequently. More important, the seemingly complex decay processes described above are really very simple when they are viewed in the context of the actual experiment. The reason is that all the neutrinos and antineutrinos produced in the decay processes are such elusive particles that the experimental apparatus simply does not "see" them at all. Thus what the apparatus actually records in each case is merely the tracks of two charged particles: either an electron and an antimuon, or a positron and a muon.

This final outcome has a distinctive experimental "signature" for two reasons. First, the appearance of an electron and a muon (or their antiparticles) in the final state seems to violate the principle of the conservation of lepton number; the rule is not really violated, however, because the undetected neutrinos make up the balance. Second, there is a lot of missing energy, but that of course is also accounted for by the unseen neutrinos.

We first began to find evidence of such electron-muon events in 1974. In a sample of 10,000 events of all types we identified 24 as electron-muon events. Al-

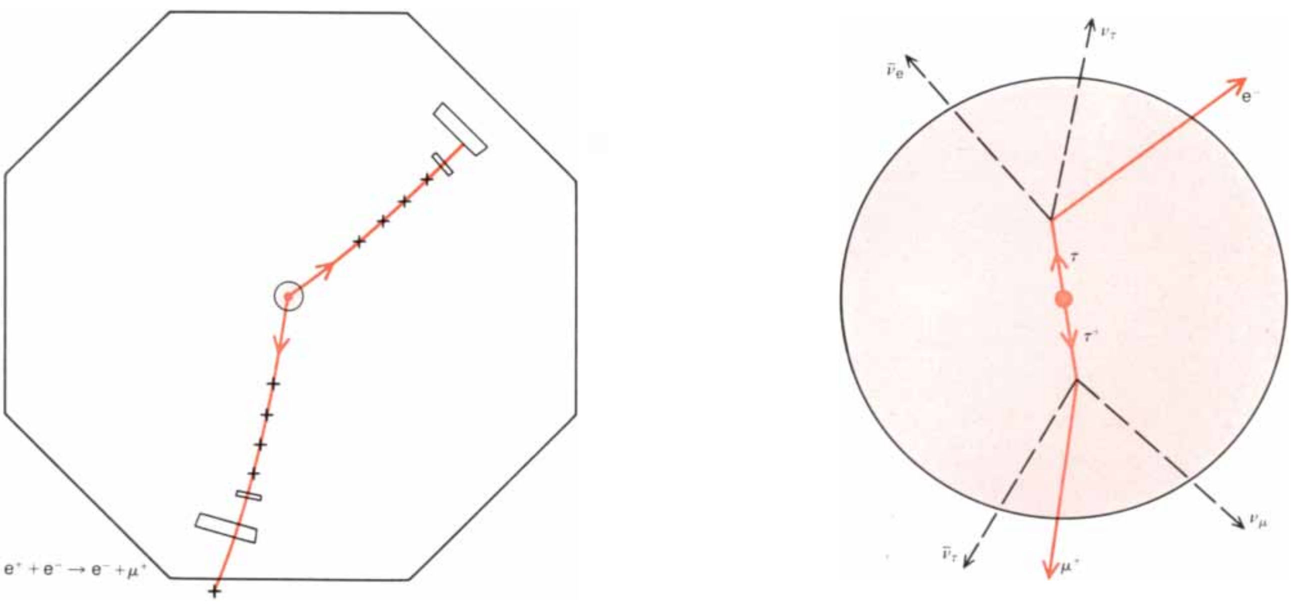


and positively charged particles curve left in the perpendicular magnetic field; hence the particle track in the eight-o'clock position is that of the electron, whereas the one in the two-o'clock position is that of the positron.) The second diagram shows a muon-muon event, in which the newly created particles are a negative muon (in the half past seven position) and a positive antimuon (in the half past one position). Unlike the electron and the positron, which lose most of their energy in generating electromagnetic showers and so cannot penetrate the iron plates, the muons pass freely through the iron and are detected in the outermost spark chambers. In the third diagram the original electron and positron annihilate each other to form a pair of hadrons, in this case a proton and an antiproton. In the fourth diagram the tracks of four hadrons are seen in the detector: two charged pions and two charged kaons. A fifth particle, a neutral pion, is also produced in this annihilation reaction, but since it is uncharged it cannot be detected directly. None of the hadrons are capable of penetrating the iron plates. The formulas with the pictures describe interactions in a shorthand notation commonly used by particle physicists.

though the number of such events was low, we were encouraged, because if the events were real, it meant that the mass of the tau was within the energy range of the SPEAR system.

At that early stage, however, we had to maintain a skeptical attitude, because with just 24 events there were various ways we could be wrong. First of all, our detector was far from perfect in identifying electrons and muons. Indeed, about 20 percent of the time it misidentified a hadron as either an electron or a muon. A careful study of the problem indicated, however, that only five or six of the 24 events could possibly be attributed to a misidentified hadron among the decay products.

A second reason for skepticism was the fact that although we might have found a new particle, it might actually be a new hadron rather than a new lepton. As it happened there was at that time a prime candidate for such a new



TYPICAL ELECTRON-MUON EVENT observed recently in the charged-particle detector at SPEAR is shown in the diagram at the left. The telltale "signature" of such an event is the detection of one particle that traverses the iron plates (the muon) and another that does not (the electron). The event is interpreted in the greatly enlarged view at the right in terms of the hypothesis that the electron and the muon come from the weak decay of a tau-antitau pair. The creation and decay of the heavy leptons happen within a few millimeters of the center of the detector and hence cannot be seen directly. Each tau particle decays into one charged particle and a pair of neutrinos; only the charged particles, in this case a negatively charged electron and a positively charged muon (or antimuon), are detected.

hadron: the charmed hadron called the *D* meson, which had not yet been discovered. It was conceivable that the electron-muon events might be coming from the production and decay of *D* mesons, accompanied by neutrinos and neutral *K* mesons. The neutral *K* meson is peculiar in that half of the time it decays so slowly that it would have escaped from our detector before the decay took place. In that case, if both of the neutral *K* mesons happened to escape, one would see only the electron and the muon in the detector and one might then be misled into thinking that the decay of a tau-antitau pair had actually been observed. As we accumulated more electron-muon events, however, particularly at higher energies, our colleague Gary J. Feldman was able to demonstrate that most of the electron-muon events could not have come from the production of *D*-meson pairs, because there were too few cases in which we observed both the electron-muon signal and the expected decay products of the neutral *K* mesons.

In the two years following our initial discovery we continued to collect more electron-muon events (we now have about 200) and to look for other ways of testing our data. One important test was to see whether the energy distribution of the electron and the muon was what one would expect from the weak decay of a heavy lepton into three particles. We found that the data did fit the three-body hypothesis well but that it did not fit the alternative two-body hypothesis [*see illustration below*].

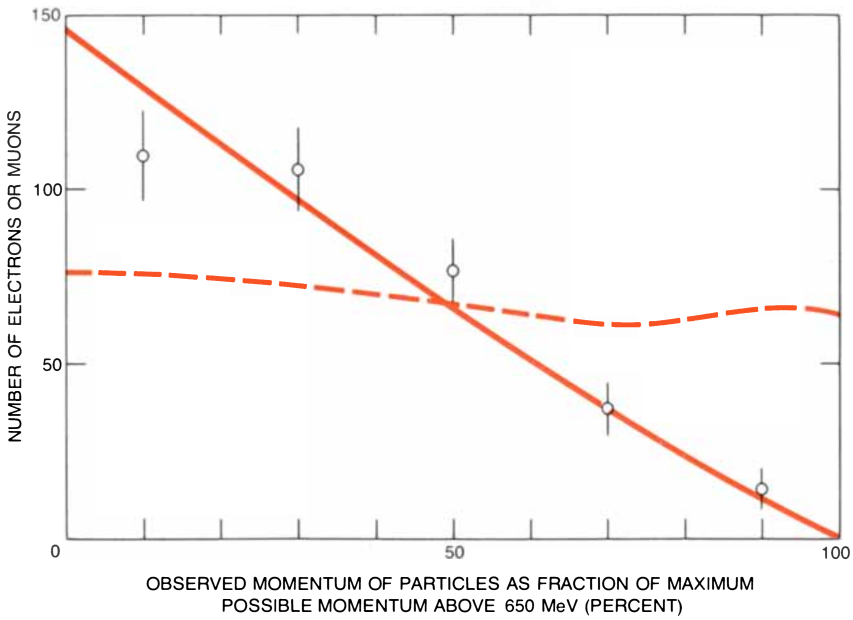
In another test we considered other possible decay modes of the tau-antitau pair. If, for example, one of the tau particles were to decay into a meson (mesons are a subclass of the hadrons) and the other were to decay into a muon, then one would expect to see distinctive muon-meson events. Such events would be distinctive because, like the electron-muon events, they would seem to violate the principle of the conservation of lepton number. A group of physicists from the University of Maryland, the University of Pavia and Princeton University found a few such muon-meson events in an experiment at SPEAR, and later our Stanford-Berkeley group was able to collect about 100 similar events.

Certain other links remained to be closed in the chain of evidence. The German Electron Synchrotron Laboratory in Hamburg has an electron-positron storage ring called DORIS, which has a particle-producing capability similar to SPEAR's. If tau particles were being created in the Stanford device, they should also be created in the Hamburg one. For a year or so there were no reports of heavy leptons being found at DORIS, but then a group at the Hamburg facility began to observe electron-muon events and later muon-meson events; in both cases they had the characteristics expected for the tau-antitau pair. Additional confirmation was provided when another group at DORIS discovered a number of electron-meson events, which are analogous to the muon-meson events.

At an international meeting on the physics of leptons and photons held last August in Hamburg five experimental groups working at SPEAR and two groups working at DORIS reported the results of their independent searches for heavy-lepton production in electron-positron annihilation. All the groups agreed on the following points: (1) that they had evidence for a new particle, (2) that the new particle was not a charmed hadron, (3) that the mass of the new particle was between 1,800 and 1,900 MeV (close to 20 times the muon's mass and 4,000 times the electron's) and (4) that all the measured properties of the new particle were consistent with the properties one would expect for a heavy charged lepton.

One way of showing that the new particle is a lepton and not a hadron is to measure its rate of production as a function of the total energy of the electron-positron collision. From studies of the production of pairs of hadrons it is known that when the total energy of the system is raised above a certain threshold energy, the production rate first increases for a time and then begins to decrease rapidly. The rapid decrease ensues because when there is too much energy available, the hadrons, which are composite particles, cannot hold together. Instead of a pair of hadrons many hadrons are produced. In contrast, since leptons are pointlike particles that do not break up, one would expect the production rate of leptons to rise rapidly from the threshold energy, reach a maximum and then decrease rather slowly as the energy is increased. Using the electron-muon events as a measure of the production rate of tau-antitau pairs, we have determined that the production rate of the new particles changes with increasing energy in the manner predicted for lepton pairs and not in the manner predicted for hadron pairs [*see illustration on opposite page*].

Although all the experiments to date agree that there is a new heavy lepton, there is still much we do not know about it. For example, the existing data are consistent with the idea that the tau is not affected by the strong force, but this insensitivity has not been tested as thoroughly for the tau as it has been for the electron and the muon. In addition many of the elementary particles, including the leptons, are in a state of perpetual rotation about their own axes, like spinning tops, but it has not yet been established that the tau has the same spin characteristics as the electron and

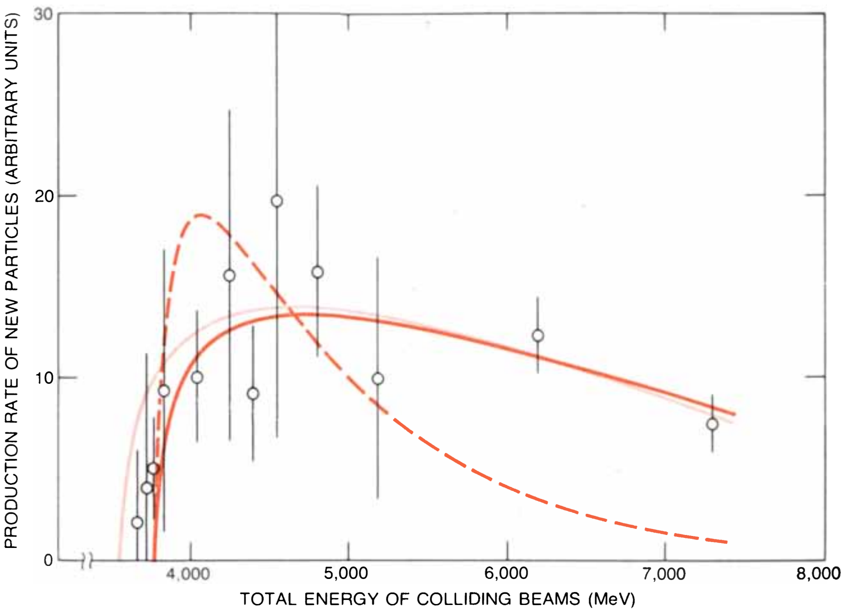


EVIDENCE in support of the conclusion that the newly discovered elementary particle is indeed a lepton and not some novel kind of hadron is presented in this graph of the energy distribution of the particles observed emerging from the distinctive electron-muon events. Only events in which the momentum of both the electron and the muon were above a certain value (650 MeV) were considered. Assuming that the tau is a heavy lepton that decays weakly into three particles (either an electron and two neutrinos or a muon and two neutrinos), the data would be expected to follow the solid colored curve. If the tau were another kind of particle that decays into an electron or a muon, in either case accompanied by a single undetected neutral particle, then the data would follow the broken colored curve. The observed energy distribution is consistent with the three-body hypothesis and not with the alternative two-body hypothesis.

the muon. We also do not know yet whether the tau is the sequential heavy lepton we initially set out to find. In other words, does the tau have its own unique tau lepton number, or taulikeness, or is it an entirely new kind of lepton with even more peculiar properties?

Experiments at other laboratories based on the interactions of muon neutrinos do not seem to have created any tau particles; hence it is unlikely that the tau is muonlike. Nevertheless, there remains the possibility that it is electronlike. (If it is, however, there must be a rather special and complicated mechanism at work to suppress the expected electromagnetic decay of the tau into an electron and a photon.) Furthermore, not all the possible decay modes of the tau have been observed, and it is only through knowing the full set of decay modes that one can know just what kind of lepton the tau is.

Another area that will require further experimental and theoretical study is the question of why the mass of the tau (between 1,800 and 1,900 MeV) is so close to the estimated mass of the charmed *D* meson (1,865 MeV), particularly when there is strong evidence that the tau is itself not a charmed hadron. As it happens, there is another such puzzling correspondence in particle physics: the mass of the muon (106 MeV) is quite close to the mass of the pi meson, or pion (140 MeV). Are these merely chance coincidences or is there some unknown relation between the masses of the leptons and the hadrons?



FURTHER EVIDENCE that the tau is a lepton and not a hadron is presented in this graph, in which the rate of production of the new particle is plotted as a function of the total energy released in the electron-positron collision. If the new particles were hadrons, then as the total energy of the system is raised above a certain threshold energy their production rate would be expected to first increase for a time and thereafter decrease rapidly (*broken colored curve*). If the tau particles were leptons, however, their production rate would rise rapidly from threshold energy, reach a maximum and then decrease slowly as the energy is increased (*solid colored curves*). Again the data are consistent with the heavy-lepton hypothesis and not with the alternative hypothesis. The dark colored curve is based on the assumption that the mass of the new lepton is 1,900 MeV; the light colored curve is based on the assumption that the mass of the new lepton is 1,800 MeV. The data suggest that the actual mass lies between the two values.

There are other questions. For example, what determines the masses of the leptons? It is hard to make sense of the observed mass sequence of the electron, the muon and the tau: .51, 106 and 1,800 to 1,900 MeV. The numbers increase too quickly to be an arithmetic series and too slowly to be a geometric series. Of course, given only three points, there are many empirical formulas that could be found to fit the sequence, but none of them would be based on a fundamental understanding of the leptons, since no one knows what accounts for the individual masses of the leptons.

And what is one to make of the properties electronlike, muonlike and taulike? Perhaps there is nothing further to understand about these properties. Just as physicists have come to accept electric charge as a fundamental property of particles for which they have no deep understanding, so too they may simply have to accept the unique lepton properties electronlike, muonlike and taulike. It is still not known why the total electric charge is conserved in all particle interactions; perhaps it is not possible to know why the total lepton numbers are conserved in all lepton reactions.

Answers may nonetheless be in the offing. Two new high-energy electron-positron colliding-beam accelerators are now under construction: the PEP machine at SLAC and the PETRA machine in Hamburg. Both devices will achieve an energy of 18,000 MeV or more per beam, which means that the search for additional charged leptons can be extended up to masses perhaps five times greater than the present upper limit of about 3,500 MeV. Most of the experiments being planned for PEP and PETRA include in their design ways to search for new heavy leptons, usually by looking for electron-muon events. Whether or not new leptons are found it is certain that the search will be more difficult, if only because the electron-muon events from the decay of the tau particles will be an annoying background. Experimenters will have to distinguish new and interesting electron-muon events from old and uninteresting ones resulting from the tau-antitau decay. On the other hand, the electron-muon events from the taus will be helpful in checking out the new devices.

Finally, there is a deeper question for which no answer exists at present. What is the relation between the two multimember classes of particles that now seem truly elementary, the leptons and the quarks? Before the discovery of the tau particles there were only four known types of lepton and four known types of quark (counting each particle and its antiparticle as one type). There was a nice symmetry here, and certain theories relating the leptons and the quarks made use of it. With the discovery of the new heavy lepton, however, the symmetry is destroyed; there are now more known leptons than there are known quarks, two more if the tau is sequential with its own tau neutrino.

Meanwhile, however, a group of physicists at the Fermi National Accelerator Laboratory (Fermilab) has recently reported evidence of the possible existence of a new, fifth kind of quark. Thus the number of quarks may also be increasing. Some theories preserve the symmetry between the leptons and the quarks, others forgo the need for such a symmetry, but almost all provide for the possibility of additional quarks and leptons. This apparent proliferation in the types of leptons and quarks, although still a matter of speculation, is somewhat alarming. In many ways it would be preferable if the truly elementary particles could remain as few in number as they were in the pre-tau days, or better yet in the pre-tau and pre-charmed-quark days. One cannot, however, dictate to nature what the fundamental constituents of matter should be. One can only hope to be up to the task of finding the constituents and understanding them.