Nobel Prize in Physics Goes to Frederick Reines for Detection of the Neutrino . . .

In the 1950s Reines and Cowan sought and found the hypothetical particle postulated by Pauli in 1930. Four decades later (two decades after Cowan's death) Reines is being honored for this feat.

The Royal Swedish Academy of Sciences has awarded the 1995 Nobel Prize in Physics "for pioneering experimental contributions to lepton physics." The prize will be shared by Frederick Reines of the University of California, Irvine, for the detection of the neutrino and by Martin L. Perl of the Stanford Linear Accelerator Center for the discovery of the tau lepton.

The academy commends Reines and the late Clyde L. Cowan Jr for their pioneering contributions during the 1950s that "led to their being able to demonstrate experimentally the existence of the antineutrino of the electron." The academy notes that Reines and Cowan's first observation of neutrinos "opened the doors to the region of 'impossible' neutrino experiments. . . . While Reines and Cowan in the 1950s managed with about half a cubic meter of water in their detector, large-scale experiments in the 1990s use many thousand cubic meters. Some experiments have even used surrounding sea or ice as their detector volume."

Wolfgang Pauli in 1930 introduced the idea of a neutrino to account for a certain puzzle in beta decay. The electrons emitted by a radioactive nucleus displayed a continuous energy distribution. The two-body decay of a nucleus at rest would produce electrons only at one fixed energy. The puzzle: How to account for the missing, variable energy? Furthermore, once nuclear spins were found, it was clear that angular momentum also wasn't being conserved.

Some physicists, including Niels Bohr, proposed that the laws of conservation of energy and momentum on a submicroscopic scale might have to be abandoned. But Pauli, in a letter to colleagues attending a meeting in Tübingen, said he had hit "on a desperate remedy to save the laws of conservation"—neutral particles with spin-½. The continuous beta spectrum could be explained by the emission of the electron and the neutral particle to carry away the missing energy and angular momentum. In 1934 Enrico Fermi used the neutrino hypothesis to formulate a theory of the weak interactions that employed Pauli's hypothesis that every time a nucleus emits an electron, a neutrino is created simultaneously.

The idea of detecting the hypothetical neutrino was appealing, but the weak interactions are so weak that a 3-MeV neutrino, for example, could penetrate a layer of liquid hydrogen a hundred light-years thick before it was captured.

How to catch a neutrino

In an article published in 1965, Cowan described the years following Pauli's and Fermi's work: "The search for the neutrino turned to indirect methods . . . [The] observations of conservation of energy and momentum, *assuming* the existence of a neutrino, became a popular argument *for* the existence of the tiny particle. The concept of the neutrino had been developed to save the conservation laws. The fact that the concept then permitted their retention . . . was then taken as proof of the existence of the neutrino. This circular reasoning is the sort that postulates the existence of a poltergeist to explain the unattended movement of a chair across the room, then takes the observed movement of the chair as proof of the existence of the poltergeist."[1] In 1950–52 a number

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. . . and Martin Perl Wins for Discovering the Tau Lepton

The discovery of a third charged lepton, 20 years ago, gave us the first glimpse of a third "generation" of fundamental particles.

Sharing this year's physics Nobel Prize with Frederick Reines (see the previous news story) is Martin L. Perl, a professor at the Stanford Linear Accelerator Center (SLAC). The Swedish academy cites Perl "for the discovery of the tau lepton," in 1975.

The tau belongs to the very exclusive club of the leptons. We know of only six species of leptons (plus their antiparticles), and we now have very good reason to believe that's all there are. Three of them—the electron, the muon and the tau—are electrically charged particles that appear to be identical except for their great disparity in mass. The other three—the three neutrino varieties corresponding to the three charged leptons—are massless, or very nearly so, and electrically neutral. All the leptons are, by definition, spin-½ particles impervious to the strong nuclear force, and they all appear to be point particles, with no evidence of any spatial extension.

The gradual realization, in the late 1940s, that the muon was just a heavier replica (about 207 times heavier) of the electron elicited from I. I. Rabi, Perl's thesis adviser at Columbia University, the famous quip, "Who ordered that?" The situation was quite similar in 1974 when Perl began searching for a still heavier replica of the electron and muon at SLAC's just-completed SPEAR electron–positron collider. There was, at that time, no good reason to expect a third charged lepton. As Perl's Stanford collaborator Gary Feldman (now at Harvard) puts it: "The tau was the last particle physics discovery that was completely unanticipated by the theorists." It turned out to be about 17 times as massive as the muon. Twenty years later, the ratios of the charged lepton masses are still not understood.

The first tentative reports of the tau discovery, in the summer of 1975, actually muddied an appealingly symmetrical picture of the "fundamental fermions"—the leptons and their associated quarks—that had been rounded out nicely with the first evidence of the charmed quark, also from SPEAR, in November 1974. That

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had observed the neutrino, Reines and Cowan sent Pauli a telegram. Pauli interrupted the meeting he was attending at CERN to announce the discovery. The text read: "We are happy to inform you that we have definitely detected neutrinos from fission fragments by observing inverse beta decay of protons. Observed cross section agrees well with expected six times ten to minus forty-four square centimeters." Pauli drafted a night letter to Reines and Cowan that Reines only saw 30 years later (when Charles P. Enz, a student of Pauli's, sent him a copy). Pauli had written: "Thanks for message. Everything comes to him who knows how to wait."

Some particle physicists have criticized these pioneering experiments of Reines and Cowan because the measured cross section for fission electron antineutrinos on protons changed with time. The initially measured value agreed with that predicted by the four-component neutrino theory of the day. But as Reines and Cowan improved their experiment, they later reported[4] that their measured cross section agreed with the new two-component neutrino theory. In an article published in *Science* based on the talk he gave at the Cowan symposium, Reines wrote that the original predicted value was based on the belief that parity is conserved in weak interactions.[3] "In view of the large experimental errors and the poorly known electron antineutrino spectrum," he explained, "we considered this [initial] crude agreement consistent with the electron antineutrino origin of the signal and continued our program to make this comparison more precise. (Our initial analysis grossly overestimated the detection efficiency with the result that the measured cross section was at first thought to be in good agreement with prediction.) . . . [The] effect of parity nonconservation is to increase the predicted cross section by a factor of 2."

Reines's background

Reines received an ME in 1939 from Stevens Institute of Technology in Hoboken, New Jersey, and a PhD in theoretical physics in 1944 from New York University, where his thesis was on the liquid-drop model of nuclear fission. Before he finished writing his thesis he left NYU to work on the Manhattan Project at Los Alamos. He remained at Los Alamos until 1959, when he became a professor and head of the physics department at Case Institute of Technology in Pittsburgh. While there he worked in reactor neutrino physics, searched for double beta decay, did electron lifetime studies, searched for nucleon decay and did an experiment in a South African gold mine that detected neutrinos produced in the atmosphere by cosmic rays. In the course of this research Reines's group pioneered in the use of labs deep underground.

Since 1966 Reines has been a professor of physics at the University of California, Irvine, where he was the first dean of physical sciences. His group at Irvine has been very active in neutrino physics and was the "I" in the IMB proton decay experiment. The IMB experiment and the Kamiokande experiment, in Japan, simultaneosly observed the neutrino burst from supernova 1987A.

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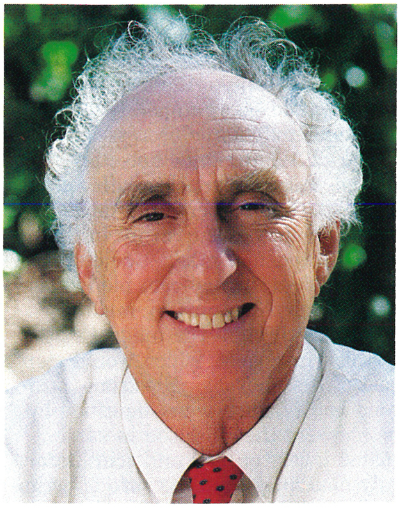
discovery completed a tidy pattern of four leptons and four quarks. Theorist Sheldon Glashow had in fact predicted the existence of the charmed quark by invoking just that sort of quark–lepton symmetry. So the tau found itself an unwanted, as well as unanticipated, intruder. Not until 1977, when the first evidence of a fifth quark (the bottom quark) surfaced at Fermilab, was the tau clearly seen as the harbinger of a "third generation" of quark pairs and their associated leptons. The announcement of the top-quark discovery last March (see PHYSICS TODAY, May, page 17) finally completes the picture.

'That's where the future is'

Having completed his PhD thesis in 1950, on atomic-beam measurements of nuclear quadrupole moments, Perl followed Rabi's advice and went into high-energy physics. "That's where the future is," said his mentor. Perl joined the University of Michigan faculty and did pion scattering experiments at the Berkeley Bevatron. One of his first graduate students was Samuel Ting, who would share the 1976 Nobel Prize for the 1974 discovery of the first of the charmed-quark bound states. Now that Perl has his own Nobel Prize, "I'm not scared of Sam any more," he told us in humorous reference to Ting's formidable reputation.

In 1964 Perl was lured to Stanford by the promise of unprecedentedly high electron-beam energies at the two-mile-long Stanford Linear Accelerator, then under construction. He wanted to crack the "electron–muon" puzzle: Why should there be two identical charged leptons with such wildly different masses? With the SLAC electron beam, Perl hoped to uncover some small telltale difference in the fundamental interactions of the two species. (There are of course uninteresting differences, such as phase-space considerations and magnetic moments, that depend trivially on mass.) "After several years of experiments at the linac I realized this wouldn't get anywhere," Perl told us, "because the techniques for studying muons and electrons were so different. There would always be a large relative error."


L. A. CICERO

MARTIN L. PERL

He needn't have felt bad. With all the new techniques and accelerators available since the 1960s, no one has yet found any nontrivial respect in which the electron, the muon and even the tau differ from one another. This extraordinary identity, called lepton universality, is a central feature of the particle theorists' "standard model."

Cornucopia at SPEAR

In 1973 the SPEAR storage ring was ready to receive electrons and positrons from the two-mile linac. Eventually the collider would run with countercirculating beam energies as high as 4 GeV, providing e^+e^- collision energies of up to 8 GeV. There were many things that could, and would, be done with such a marvelous new facility. But Perl's main focus was on the possibility of finding new, heavier leptons, made in particle–antiparticle pairs by e^+e^- collisions.

Perl was part of a SLAC–Berkeley collaboration that built and took data with a general-purpose particle detector around one of the two points at which the SPEAR beams collide. He, in particular, was searching for e^+e^- collisions that produced an electron or a positron, together with a muon of the opposite sign, but no other particles that the detector could see. A putative heavy lepton L^-, he reasoned, could decay with equal probability into an electron or a μ^- after traveling a fraction of a millimeter. Either of these leptonic decay modes would also produce an undetectable pair of neutrinos. Therefore, to find the reaction

$$e^+ + e^- \rightarrow L^+ + L^-$$

Perl scoured the data for collision events producing $e^\pm + \mu^\mp$ accompanied by nothing else except missing momentum and energy. He ignored, for the time being, the equally probable $e^+ + e^-$ and $\mu^+ + \mu^-$ decay modes, because they, unlike the $e^\pm + \mu^\mp$ events, would be swamped by conventional electrodynamic processes.

The SLAC–Berkeley detector tracked charged particles with an array of spark chambers, and measured their momenta by curvature in the detector's solenoidal magnetic field. It distinguished muons from pions and other charged hadrons by making them pass through the magnet's 20-cm-thick iron yoke, which would stop most of the hadrons. Electrons, positrons and photons were identified by the showers they induced in sandwiched layers of lead and scintillator. Only neutrinos could be sure of escaping detection.

By the summer of 1975, having sifted through some 40 000 events at collision energies ranging from 4 to 5 GeV, Perl had come up with a grand total of 86 $e^\pm\mu^\mp$ events with nothing else detected except missing momentum and energy. But how much of this could he attribute to heavy leptons or other new physics? "Ours was by no means a state-of-the-art detector," Perl told us. "It left about a third of the solid angle uncovered. There were lots of holes through which photons from π^0 decay could sneak out, and the iron yoke was too thin to stop all the hadrons."

Skeptics

Before he set out to convince the world, Perl had to convince his somewhat skeptical collaborators, most of whom had been watching his largely solo effort at a distance while they were busy pursuing the spectroscopy of the charm–anticharm bound states that were tumbling out of the detector in exhilarating profusion. But he eventually convinced them that no more than a quarter of his 86 events could be attributed to particle misidentification or hadron decay. At that point Perl and his collaborators published their first tau paper.[1] But they had not yet given the baby a name, nor had they definitively declared it a lepton. "We conclude," they wrote, "that the e–μ events cannot be explained . . . by any presently known particles. . . . A possible explanation is the production and decay of a pair of new particles, each having a mass in the range of 1.6 to 2.0 GeV."

A complicating issue was the discovery at SPEAR of the D^0, the lightest of the charmed mesons, by Gerson Goldhaber and other members of the SLAC–Berkeley collaboration in the spring of 1976. With a mass of 1865 MeV, the short-lived D^0 was obviously being produced in pairs at about the same SPEAR energies as Perl's putative new lepton. "For those of us who looked closely at the data, it was soon clear that Martin's e–μ sample couldn't be seriously contaminated by charmed-meson production," recalls Feldman. "There just wasn't enough evidence of hadrons, and the momentum distributions clearly favored the kinematics of two-neutrino lepton decay." The lepton hypothesis was further strengthened by augmenting the detector's electron and muon identification capability with the installation of a lead glass wall and a two-meter thickness of concrete hadron absorber.

Nonetheless, at conferences in Europe that summer Goldhaber's D^0 was the big news, and the Europeans were still quite skeptical about Perl's lepton, primarily because it hadn't been seen at DORIS, the new electron–positron collider in Hamburg. "Everyone knows that Perl always wanted to find a heavy lepton," one unbeliever told Feldman, "and people delude themselves into finding what they look for." When Feldman expressed concern that the collaboration was not making its case effectively to the Europeans, Perl responded: "It's not important. The great thing about science is that it doesn't matter what people think. The truth comes out in the end."

And so it did. By the summer of 1977 the new lepton had been seen at DORIS, and the time had come to give it a proper name.[2] To that end the SLAC–Berkeley collaboration was fortunate to have a Greek graduate student, Petros Rapidis, who pointed out that τ could stand for $\tau\rho\iota\tau o\nu$, the Greek work for "third." "Tau" did have an older, already obsolete meaning in connection with kaon decay. But it was argued that Greek letters were too valuable not to be recycled.

The three-generation family tree heralded by Perl's discovery of the third charged lepton offers the most natural explanation for *CP* violation, the small but important asymmetry of the weak interactions under the combined operations of charge conjugation and parity inversion. Only with three or more generations can one explain this symmetry violation in terms of an overall phase angle in the mixing matrix that relates the quark mass eigenstates to their weak-interaction eigenstates.

Could there be a fourth generation lying in wait? Not very likely. In recent years extensive measurements at LEP, the gargantuan high-energy e^+e^- collider at CERN, have narrowly constrained the invisible decay modes of the Z^0, one of the triumvirate of heavy gauge bosons that mediate the weak nuclear force. With a minimum of theoretical assumptions, these measurements tell us that the number of light neutrino species in the universe is 2.983 ± 0.025.

'It's called physics'

Perl was born in Brooklyn, New York, in 1927. After brief stints in the Coast Guard and the Army he received his bachelor's degree in chemical engineering from Brooklyn Polytechnic Institute in 1948. He then went to work in General Electric's tube division in Schenectady, New York, where he took several courses at Union College in his spare time. "I had a wonderful atomic physics teacher named Vladimir Rojansky at Union," recalls Perl. "One day he said to me, 'There's a name for what you're really interested in, Martin. It's called physics.' So I applied to Columbia and was accepted as a graduate student in physics. I had almost none of the prerequisites, but in those days it was much easier to catch up."

Nowadays Perl is involved in experiments at CESR, the 10-GeV electron–positron collider at Cornell. "Most of my SLAC colleagues," he told us, "are busy getting ready for the B factory," the next-generation asymmetric e^+e^- collider now under construction at Stanford. (See PHYSICS TODAY, April 1995, page 65 and December 1990, page 20.) "But that won't be providing data for another four or five years, and I'm 68 years old."

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