

## 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- $\frac{1}{2}$ . The continuous beta spectrum could be explained by the emis-

sion 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."<sup>1</sup> In 1950–52 a number

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

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- $\frac{1}{2}$  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

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

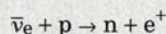
similar in 1974 when Perl began searching for a still heavier replica of the electron and muon at SLAC's just-completed SPEAR electron-positron collider. There was, at that time, no good reason to expect a third charged lepton. As Perl's Stanford collaborator Gary Feldman (now at Harvard) puts it: "The 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 muddled 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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of people who had been doing nuclear bomb testing wondered if the bombs could also be used for physics research. For example, could a bomb be used as a high-flux source of neutrinos that could then be observed? Some months after Reines received encouragement from Fermi to try using a bomb to detect the neutrino,<sup>2</sup> Reines and Cowan, who were then at Los Alamos, decided to try such an experiment. They chose to look for the reaction



In Reines's words, "If the neutrino exists in the free state, this inversion of beta decay must occur. We chose to consider this reaction in particular because if we believe in detailed balancing and use the measured value of the neutron half-life, we know what the cross section must be—a nice clean result. (In fact, we learned some years later from Tsung Dao Lee and Chen Ning Yang, the cross section is greater by a factor of two because of parity nonconservation.)"<sup>2</sup>

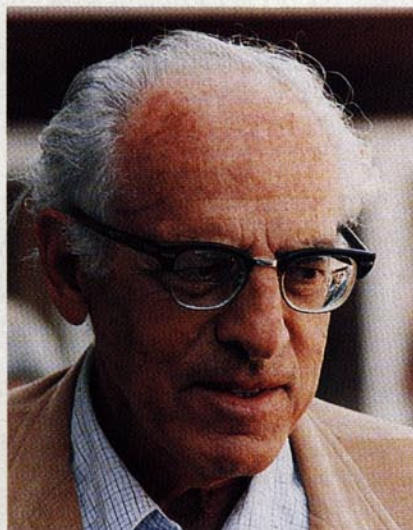
Reines and Cowan proposed building a shaft near the site where the bomb was to be detonated and suspending a detector in the shaft. Just before detonation, the shaft would be evacuated, and when the countdown reached zero, the suspension would be broken and the detector would fall freely. "As it made little difference precisely where we placed our shaft, we chose to put it 137 feet from the base of the tower for luck," Cowan wrote.<sup>1</sup>

In the fall of 1951 Reines and Cowan gave a seminar at Los Alamos, describing their plans to use a bomb to look for the neutrino. At the end of the talk, J. M. B. Kellogg, chairman of the physics division, suggested that they review the problem again to see if they could use neutrinos from a fission reactor instead of a fission explosion. Reines and Cowan had been planning to use the two 0.51-MeV gammas to signal positron annihilation; the gammas would be observed by the scintillation they produced. The neutron would be captured by a proton and release a 2.2-MeV gamma, and that delayed gamma would serve as an independent signal.

Suddenly the researchers realized they could dissolve a cadmium salt in the liquid and the cadmium could enhance the neutron capture. The neutrino signal would be two characteristic bursts of gamma radiation—first the two 0.51-MeV gammas, then a burst of gammas totaling about 9

MeV as the neutron was captured by the cadmium. In Cowan's words: "It would then be possible to use the much weaker but calmer neutrino fluxes emitted by a reactor. Instead of detecting a burst of neutrinos in a second or two . . . we would now be able to watch patiently near a reactor and catch one every few hours or so."<sup>1</sup> In describing Reines's work the Swedish academy notes, "Despite the great intensity of the neutrinos the reactor delivered, such a low counting speed was expected for this reaction that the attempt appeared to be bordering on the impossible."

Reines and Cowan conducted their first experiment to search for the free neutrino at the Hanford reactor in Hanford, Washington. The winter of 1953 found the experimenters testing their system in a remote, unheated building, and they had to heat their detector. But the background radiation was too great at the Hanford re-



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actor, and the neutrino signal was at best a two-standard deviation effect. Cowan later wrote, "We felt that we had the neutrino by its coattails, but our evidence would not yet stand up in court."<sup>1</sup>

Reines and Cowan then designed a more sophisticated detector that would exploit the detailed characteristics of the inverse beta decay and thus discriminate more selectively against backgrounds from the reactor and the surroundings.

### Search moves to Savannah River

In 1955, at the suggestion of John Wheeler, they took their new detector to the newly built reactor at the Savannah River facility in South Carolina.

Reines, describing the experiment at a memorial symposium for Cowan

held in 1978, said that the Savannah River reactor was admirably suited to the experiment because of its great power (about 700 megawatts at the time) and relatively small dimensions and the availability of a well-shielded location 11 meters from the center of the reactor and 12 meters below the ground in a massive building.<sup>3</sup> The high electron-antineutrino flux,  $10^{13}$  per square centimeter per second, and the reduced cosmic-ray background underground were both crucial for the experiment to succeed. Reines, Cowan and their collaborators ran the experiment for 100 days over a period of about a year.

They used about 400 liters of water containing dissolved cadmium chloride, placed between large liquid scintillation detectors. When the electron antineutrino collided with a proton in the water, the positron was slowed down by the water and then it was annihilated with an electron to produce two 0.51-MeV photons. The pair of annihilation photons were detected simultaneously in the two scintillators. Meanwhile the neutron was also slowed down in the water and eventually captured by a cadmium nucleus, causing the emission of several characteristic photons, which reached the detectors a few microseconds later than the annihilation photons.

Describing one of the tests the experimenters used to verify they were seeing antineutrinos from the reactor, Cowan wrote, "If we were seeing antineutrinos from the reactor, we should not be able to reduce their intensity on the detector by putting absorbers around it. If, on the other hand, we were seeing only gamma rays and neutrons, it should be easy to change the rate with absorber."<sup>1</sup>

The experimenters considered a variety of shields, including watermelons and sacks of hominy grits. "The native resources of the South did come to our rescue, however," explained Cowan. "We used sawdust. Obtained free from a sawmill in Aiken, SC, and bagged as it came from the chute, we hauled it in great truckloads to the reactor site. The sawdust was too light for our liking, so we piled it into a small mountain and squirted it with a firehose for several days. Drained and stacked around our detector, it provided a fine shield. In recognition of the Southern hospitality which we were enjoying all this time, we also incorporated hominy grits into the shield—a pound of it."<sup>1</sup> The shield did absorb artificial signals from neutron and gamma sources placed nearby, but, as the experimenters had hoped, it had no effect on the neutrino signal.

On 14 June 1956, convinced they



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<sup>4</sup> 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.<sup>3</sup> "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, simultaneously observed the neutrino burst from supernova 1987A.

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## References

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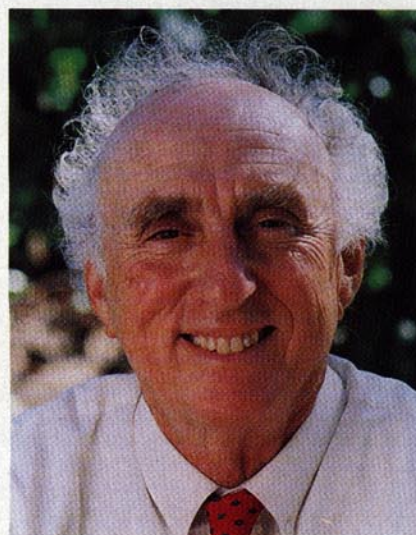
discovery completed a tidy pattern of four leptons and four quarks. Theorist Sheldon Glashow had in fact predicted the existence of the charmed quark by invoking just that sort of quark-lepton symmetry. So the tau found itself an unwanted, as well as unanticipated, intruder. Not until 1977, when the 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 formi-

dable 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."



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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