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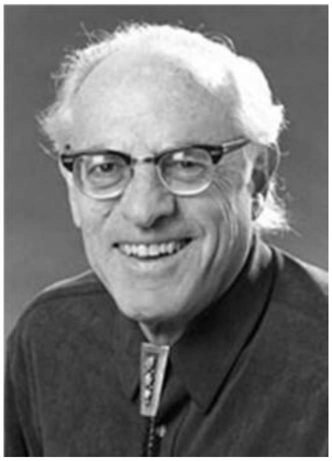
# Nobel Prize in Physics 1995

**Martin L. Perl**



**Frederick Reines**

The Nobel Prize in Physics 1995 was awarded *"for pioneering experimental contributions to lepton physics"* jointly with one half to Martin L. Perl *"for the discovery of the tau lepton"* and with one half to Frederick Reines *"for the detection of the neutrino"*.

## RESEARCH INFORMATION:

This additional background material gives a short account of the two discoveries and their importance and is written mainly for physicists.

### 1. Two breakthroughs in lepton physics

The pioneering work performed by Frederick Reines and Clyde L. Cowan, Jr., (deceased 1974) at nuclear reactors in Hanford and the Savannah River Plant during the 1950's not only led to the first experimental observation of a neutrino, but also helped to break the ground for the modern generation of low energy neutrino experiments previously considered impossible. Several of these experiments aim to detect neutrinos emanating from the sun or from supernovas. Due to the extremely small cross sections for neutrino interactions with atomic electrons and atomic nuclei a large amount of detector material is needed. Reines and Cowan performed their experiment with about half a cubic meter of fluid (mainly water with some suitable impurity) in their detector, which was considered to be a very big one at that time. Some detectors of today use several tens of thousands cubic metres of detector fluid.

The discovery of the tau lepton by Martin Perl and his team; 1974-1975 at the Stanford Linear Accelerator Center (SLAC) was the first sign of the existence of a third family of elementary constituents of matter. The results of these experiments came as a big surprise to most physicists. The first family (electron, electron neutrino, up and down quarks) had already been established by the end of the 1960's. The second family (muon, muon neutrino, charm and strange quarks) was just becoming firmly established through the discovery of the charm quark in 1974-76, at the time when the tau lepton appeared on the scene. Soon afterwards, in 1977, one of the two quarks of the third family, the bottom quark, was discovered by Leon Lederman and his collaborators, but it took almost 20 years for the completion of this family (tau, tau neutrino, top and bottom quarks). The long awaited discovery of the top quark was finally made in 1994-1995 (at the Fermi National Accelerator Laboratory, USA).

The third family of leptons and quarks would not have been so interesting if there existed a large number of such families. Recent results from the accelerator LEP at CERN, however, show that within the framework of the Standard Model there are three, and only three, families (the experimentally determined figure is 2.988 +/- 0.023). With only two families the Standard Model would have been manifestly incomplete because it would, e.g., not have allowed the observed phenomenon of CP violation. If a fourth family of quarks and leptons is discovered in the future, the Standard Model in its present form would need a revision and a major reconstruction of the theory of elementary particles could be called for. Perl can thus be said to have discovered the first member of the "last family of the Standard Model". It still remains to detect the tau neutrino.

## 2. The discovery of the neutrino

The neutrino was "born" as a hypothetical neutral particle in a letter written by Wolfang Pauli on the 4th of December 1930. It was introduced to explain the continuous electron energy spectra observed in nuclear beta-decay (by assuming the conservation of energy, momentum, angular momentum and charge) and Pauli had to assume that it only interacted weakly with its surroundings. Pauli felt that he had done something terrible by postulating a particle that, as he was convinced, never could be detected directly. As it turned out, the neutrino was in fact eventually detected, but the achievement came almost 30 years later and took all the skills of Reines and Cowan.

Soon after the neutrino hypothesis was put forward it was used by Enrico Fermi to formulate a theory for weak interactions. The success of this theory gave a great deal of credibility to the neutrino hypothesis, but how could a final proof of the existence of the neutrino be found? Hans Bethe and Rudolf Peierls, as well as others, had estimated the cross section for capturing neutrinos produced in the beta-decay of radioactive nuclei and had found that one would need a target of lead several light years thick to effectively catch these neutrinos. Thus a very intensive source of neutrinos as well as a heavy target were needed in order to establish the existence of the neutrino. When the first nuclear reactors were constructed in the 1940's, Fermi and others realized that they were high-flux sources of neutrinos. The estimated neutrino flux was as high as $10^{12}$ - $10^{13}$ per second and $cm^2$, many orders of magnitude larger than the corresponding flux from ordinary radioactive sources.

In 1953 Reines and Cowan proposed a reactor experiment to detect neutrinos. The reaction chosen to be studied was the capture of a neutrino by a proton in the target (also acting as a detector) giving a neutron and a positron; in modern terminology

$$\bar{\nu} + p \; {-}{-}{>} \; n + e^{+}.$$

Even though the flux of neutrinos from the reactor was high, the expected counting rate was so low that the experiment seemed to be on the verge of being possible. Reines and Cowan realized that it is essential to detect both the positron and the properly time-delayed neutron in order to reduce the background. In the first experiment at the Hanford reactor in 1953, Reines and Cowan observed no statistically significant neutrino signal - the background signals were too many. The experiment was re-designed and placed underground at the Savannah River Plant. The target and the photon detectors were separated for a better rejection of the background signal. A significant neutrino signal was then observed. At this reactor another physicist, Raymond Davis, Jr., had already tried in vain to catch neutrinos through a different reaction which involved producing radioactive argon atoms from chlorine atoms in a solution of carbon tetrachloride. The negative results of Davis could either be interpreted as the non-existence of free neutrinos or be explained by assuming that there actually were two kinds of neutrinos, the neutrino $\nu$ and the antineutrino $\bar{\nu}$. The experiment of Reines and Cowan was partially aimed at resolving this question.

The two targets in the Reines-Cowan experiment contained each about 200 litres of a solution of cadmium chloride ($CdCl_2$) in water. The targets were sandwiched between three scintillation detectors. The delayed coincidence technique introduced by Reines and Cowan to reduce background worked as follows: The neutrino interaction with a proton of the water created a positron and a neutron. The positron was quickly slowed down by the water and was annihilated by an electron. This annihilation created two photons, each with an energy of about 0.5 MeV. These photons were registered in coincidence in the two scintillation detectors above and below the target where the interaction took place. The neutron also slowed down in the water and was eventually captured by a cadmium nucleus. This created a few capture gamma rays of very high energies (about 8 MeV) that reached the detectors with a delay of a few microseconds with respect to the photons from the annihilation event.

The experiment was hampered by both a low counting rate, about three events per hour, and a large background. Nevertheless Reines and Cowan succeeded in their attempt to prove the existence of the neutrino as a free particle. Several publications describe the course of the experiment and the results. The definitive account of the discovery is given in Reines *et al.*, " Detection of the free antineutrino", *Phys. Rev.* 117, 159 (1960).

Reines has also been engaged in pioneering experiments probing decay modes of the proton. The big underground facilities used for this purpose can also act as neutrino detectors and give valuable information on cosmic processes. As an example, underground detectors registered neutrinos from the supernova SN1987a on the 23rd of February 1987. One of the detectors, in the Kamioka mine in Japan, registered 11 neutrinos from the supernova. Another detector, built by the IMB (Irvine-Michigan-Brookhaven) collaboration, in which Reines participated as a leading scientist, registered 8 neutrinos. These experiments provided, for the first time, astrophysicists with valuable information on supernovas as well as giving a limit for the neutrino rest mass.

## 3. The discovery of the tau lepton

During the 1960's a number of experiments looking for new charged particles were performed and several groups participated in the search. One way was to look for the new particles in the decay products of known unstable particles such as the kaons. Another method was to try to produce new particles at high energy accelerators, e.g., through photo-production in collisions between high energy electrons and a fixed target with nuclei Z:

$$e^- + Z \longrightarrow e^- + Z + \gamma + \ldots \longrightarrow e^- + Z + X^+ + X^- + \ldots.$$

Here $X^+$ and $X^-$ represent new charged particles, possibly leptons of positive and negative charges. Perl was a member of a group that performed such a photo-production experiment at a linear accelerator, which went into operation in 1966 at the Stanford Linear Accelerator Center (SLAC). The results obtained by Perl and his coworkers at this accelerator were negative: no new charged leptons were found (*Phys. Rev.* 173, 1391 (1968)). A few years later, in 1973, the electron-positron storage ring SPEAR was installed at the end of the SLAC linear accelerator. At such a collider the reaction mechanism for production of new leptons was expected to be simple and easy to interpret, viz.,

$$e^- + e^+ \Rightarrow X^+ + X^-.$$

Moreover, the probability of producing charged leptons in such collisions is relatively large, provided, of course, that they can be produced within the energy span of the accelerator. The SPEAR facility thus provided Perl with an excellent opportunity to continue the search for new leptons, this time in a new and previously inaccessible energy region. During its first years of operation the SPEAR reached a top center-of-mass energy, with useful luminosity, of about 5 GeV. The experimental equipment was designed to detect new charged leptons beyond the maximum made possible by the machine.

Already in 1974 came the first signs of the possible production of a new lepton and a year later the first results were reported in the article "Evidence for Anomalous Lepton Production in $e^- + e^+$ Annihilation" (Phys. Rev. Lett. 35, 1489 (1975)) with Perl as the first author. But it took a few more years before Perl and his collaborators, and also other research groups, could convincingly show, through a detailed analysis of data, that the observed anomalous lepton pairs were due to pair production of a new heavy lepton. The new lepton was denoted by the Greek letter tau, which is the first letter of the word triton, τριτον (which means the third); the discovered lepton being the third charged lepton, after the electron and the muon. The electron, being the lightest charged lepton with a mass of 0.511 MeV/$c^2$, belongs to the first family. The muon is about 207 times heavier (106 MeV/c2) and belongs to the second family. The tau, belonging to the third family, turned out to have a mass as large as about 1780 MeV/$c^2$, thus being about 3500 times heavier than the electron.

Searches for new charged leptons produced in collisions between electrons and positrons had been undertaken earlier by other groups of physicists. A group led by Antonino Zichichi performed an experiment at the electron-positron colliding beam facility ADONE at Frascati outside Rome. However, this accelerator, which had started operation in 1969-70, did not have enough energy to produce pairs of $\tau^+\tau^-$. Also another group at ADONE, led by Marcello Conversi, found no new charged leptons. These experiments showed that a heavy lepton, if it existed, had to be heavier than 1400 MeV/$c^2$, which was the mass limit set by the accelerator energy. Thus, in the mass range up to 1.4 GeV/$c^2$, the electron and the muon were the only charged leptons.

In the SPEAR storage ring beams of electrons and positrons were made to collide head-on inside a several metre large cylindrical detector in a strong magnetic field. The detector had several components, among them a system of scintillation counters for detecting charged particles and four concentric spark chambers for tracking particles in the magnetic field. The first sign that something new was going on came with the observation of 24 events of the type

$$e^- + e^+ \longrightarrow e^- + \mu^+ + \text{i.p.}$$

or

$$e^- + e^+ \longrightarrow e^+ + \mu^- + \text{i.p.}$$

where i.p. denotes "invisible particles", i.e. particles that left no visible track in the detector. The actual detection was thus only that of an electron (positron) and an antimuon (muon), i.e., two different leptons with opposite charges, which apparently violates the law of lepton number conservation. The researchers were looking for events where the momentum vectors of the two leptons were not found to be "back to back", thus suggesting an apparent violation of the law of momentum conservation. Using conservation of energy and momentum it was realized that at least two invisible particles had been produced together with the two charged leptons.

A possible interpretation of the above events was that a pair of unstable heavy leptons, later denoted by tau, had been produced

$$e^- + e^+ \longrightarrow \tau^- + \tau^+.$$

But since the tau leptons were expected to decay very rapidly, the observed electrons and muons could be interpreted as decay products from reactions

$$\tau^- \longrightarrow e^- \ (\text{or } \mu^-) + \text{neutrinos}$$
$$\tau^+ \longrightarrow \mu^+ \ (\text{or } e^+) + \text{neutrinos.}$$

The invisible particles were neutrinos. Owing to their weak interaction they disappeared without leaving a trace, but they could account for the energy and momentum balances and indeed took an appreciable amount of the available energy.

The heavy lepton hypothesis of Perl and his collaborators was tested through a series of observations which took several years to complete. The tau lepton stood up to the test and was shown to be a heavier relative of the electron and the muon. Its mass (1776.96 MeV/$c^2$) and lifetime (291.3 fs) are now very accurately known. Indeed the tau also has its own neutrino, the tau neutrino, as do the electron and the muon. In order to directly establish its existence, beams of tau neutrinos have to become available.

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http://www.nobelprize.org/nobel_prizes/physics/laureates/1995/advanced.html