Discoverers of the Neutrino and Tau Recognised

Particles that Acquired 'Nobelity'

K V L Sarma

The 1995 Nobel Prize in Physics is shared by the American physicists Frederick J Reines and Martin L Perl for their pioneering experimental contributions to 'lepton' physics. Leptons, such as the electron, do not feel the nuclear force but only the electromagnetic and the weak beta decay force. This year it is the turn of two of the six leptons of today's particle physics, the electron-neutrino ν_e and the τ lepton, tau, to acquire 'Nobelity'.

Frederick Reines (University of California, Irvine), now 77, with Clyde L Cowan Jr. (who died in 1974) reported the first direct evidence of the existence of the 'neutrino' in 1956. The neutrino is a tiny neutral particle hypothesized by Wolfgang Pauli Jr. in 1930. Twenty five years later and with the invention of the nuclear reactor it was possible to verify its existence.

Martin Perl (Stanford University, Stanford),

This year's Nobel award in Physics is in recognition of two landmark experiments in elementary particle physics. One provided the confirmation of the neutrino, as envisaged by Pauli more than two decades earlier. The second discovered the heavy charged lepton τ which heralded the third, and perhaps the last, generation of the ultimate constituents of matter to which the top and bottom belong. A summary of the discoveries made in the world of leptons is given in the table below. The third generation has now started getting Nobel prizes. It should be noted that ν_τ still needs to be identified experimentally (and hence the question marks in the last row of the table). For this one has to demonstrate that τ's are produced directly in collisions of ν_τ with nuclear targets.

Generation	*Lepton*	*Discoverer(s(year))*	*Nobel Prize (year)*
1	electron *e*	J J Thomson (1897)	J J Thomson (1906)
	electron-neutrino ν_e	C L Cowan *et al* (1956)	F J Reines (1995)
2	muon μ	J C Street, E C Stevenson C D Anderson, S H Neddermeyer (1936)	-----
	muon-neutrino ν_μ	G Danby *et al* (1962)	M Schwartz, L M Lederman J Steinberger (1988)
3	tau τ	M L Perl *et al* (1975)	M L Perl (1995)
	tau-neutrino ν_τ	?	?

aged 68, assisted by a 35-member team, discovered the 'tau lepton' in 1975. This particle carries one unit of electric charge and weighs approximately twice as much as a proton. It has a very short life, of only a fraction of a pico-second (millionth of a millionth of a second). Thus tau has the distinction of being 'the heaviest' and 'the shortest-lived' lepton observed. It is interesting that while Reines's neutrino results were in some sense expected, Perl's tau discovery came as a complete surprise.

Brief History of the Neutrino

Neutrinos, they are very small.
They have no charge and have no mass
And do not interact at all.
The earth is just a silly ball
To them, through which they simply pass,
Like dustmaids down a drafty hall
Or photons through a sheet of glass.

(John Updike)

The 'birth' of neutrino can be traced to a letter of 4 December 1930 written by Pauli from Zurich. He mentioned that he had hit upon the neutrino as a "desperate remedy" to save, among other things, the principle of energy conservation in beta decay. The particle was to possess no electric charge but carried the missing energy and momentum and escaped the detecting equipment. The famous beta decay theory of Fermi appeared in 1934, wherein Fermi named the Pauli particle 'the neutrino', meaning the little neutral one.

It is interesting that even the great Pauli did not fully recognize the implications of the neutrino, particularly in regard to its penetrating power. Initially he thought he had done a'frightful thing' as the neutrino was expected to have penetrating power similar to, or about 10 times larger than, a gamma ray. However in 1934 Hans Bethe and Rudolf Peierls argued that the neutrino had to be even more elusive as its interaction mean free path had to be astronomical in magnitude.

Detection of the Reactor Neutrino

The first neutrino reaction to be observed (as is customary, here we are using the word 'neutrino' in its generic sense although, strictly speaking, what Reines and his group detected were signals from the electron-antineutrino ν_e) was the reaction.

$$\bar{\nu}_e + p \longrightarrow e^{+} + n$$

driven by the antineutrinos from the nuclear reactor. This reaction is essentially the reverse of the neutron decay

$$n \longrightarrow p + e^{-} + \nu_e.$$

The underlying idea was to look for a pair of scintillator pulses; the first (prompt) pulse due to positron annihilation and the second (delayed) one due to capture of the 'moderated' neutron. The experiment was performed around 1955-56. Projectiles came from the reactor located at the Savannah River Plant, in South Carolina State, USA, and targets were the protons in a solution of water mixed with cadmium chloride (Cd is a good absorber of thermal neutrons). The experimental apparatus was a sandwich of target tanks (containing a solution of water and $CdCl_2$) and liquid scintillation detectors.

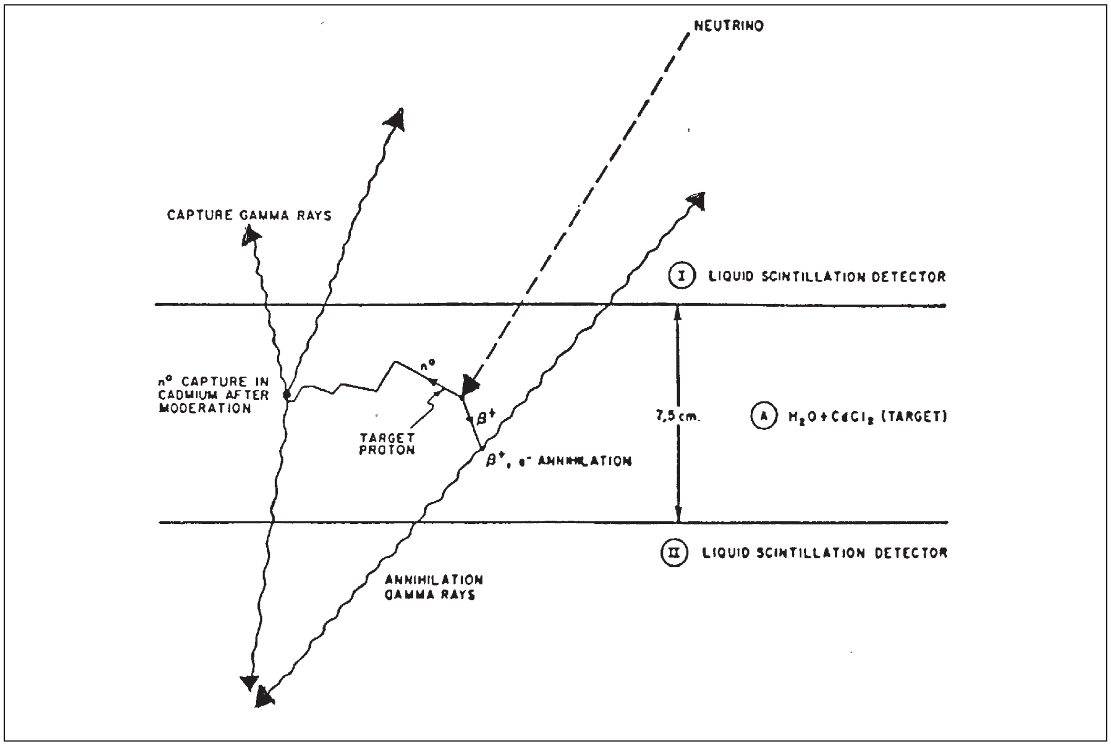


***Figure 1** Schematic diagram of the neutrino detector of the Reines-Cowan experiment.*

An event meant the detection of two prompt coincidences (see *Figure 1*): the first one was between the two photons (each having 0.511 MeV energy) of the positron annihilation, and the second coincidence was due to the capture of the neutron by cadmium giving a few photons. The second pulse occurred after several micro-seconds of the positron flash, because the neutron took that much time to degrade its energy to the level of thermal energies in the target water. The experiment involved, among other things, measuring energies of the pulses, their time-delays, etc. The observed signal did vary with the reactor power output, and hence with the neutrino flux. It gave an average rate of 2.88 ± 0.22 counts/hour, consistent with the value that is expected from the inverse beta reaction. In this way the neutrino was experimentally verified.

We know very little in regard to the electron-neutrino (and even less about other neutrinos). As for its rest mass, data on the end-point of the beta electron spectra only show that it cannot exceed a few eV. An important feature of ν_e is that it is *left-handed*: the spin of the neutrino, which has a magnitude of half a natural unit, is observed to be aligned *opposite* to the momentum direction. This intrinsic property of the neutrino was discovered in 1958 in an exceedingly clever experiment performed by Goldhaber, Grodzins and Sunyar.

Experimental data using the ν_e's are not extensive because it is difficult to obtain ν_e beams. The sun is a good source of ν_e but the solar neutrino fluxes are not well understood and constitute one of the challenging problems of current research. Recently the first experiment using a man-made source of pure ν_e was performed. It made use of an intense source of reactor-produced ^{51}Cr (which emits ν_e by electron capture) to calibrate the GALLEX solar neutrino detector located in Italy.

Discovery of the Tau Lepton

Tau is a heavier electron. It entered the scene unexpectedly in 1975. While the results of Reines needed the construction of power reactors, the discovery of the tau lepton needed high energy electron-positron colliders. Tau lepton is the third kind of charged lepton that exists in nature, the other two being the electron and the muon. (The Greek letter τ is the first in the word triton, meaning third).

The experiment was performed at the electron-positron collider called SPEAR (Stanford Positron Electron Accelerator Ring), where beams of e^- and e^+ were accelerated simultaneously in opposite directions in a ring and made to intersect. As the total center-of-mass energy (the sum of beam energies)

$$E_{cm} = E_{e-} + E_{e+} = 2E_{e-},$$

was tunable in the range 3-8 GeV, a pair of charged particles each having a rest mass of about 2 GeV could easily be produced at SPEAR.

Anomalous Events: The 'anomalous' events reported by Perl and collaborators corresponded to the following reactions

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

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

where 'i.p.' denotes invisible particles which left no trace in the detector. The ingenuity of the experimenters consisted in establishing that the oppositely-charged $e\mu$ pair was the result of separate decays of two new particles which were oppositely-charged and short-lived. At the energy $E_{cm} = 4.8$GeV there were 24 events (13 $e^+\mu^-$ and 11 $e^-\mu^+$).

The occurrence of anomalous events as a function of E_{cm} exhibited an increase around 4 GeV, indicating a threshold for producing them. The events were interpreted as proceeding from the reaction

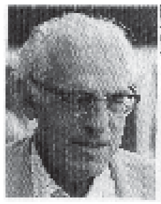
$$e^+ + e^- \longrightarrow \tau^+ + \tau^-,$$

where the taus decayed immediately into lighter leptons. A new conservation law called the 'tau-lepton number' conservation is assumed. According to this, in the τ^- decay, a neutrino called the tau-neutrino (ν_τ) is always emitted; in the τ^+ decay a tau-antineutrino (ν_τ) is emitted. Thus the anomalous event with, say, $e^-\mu^+$ was the result of decays

$$\tau^- \longrightarrow e^- + \bar{\nu}_e + \nu_\tau$$
$$\tau^+ \longrightarrow \mu^+ + \nu_\mu + \bar{\nu}_\tau$$

wherein the two neutrinos and the two antineutrinos constitute the invisible particles denoted earlier by 'i.p'.

1995 Nobel Laureates in Physics



Frederick Reines

Martin L Perl

Data gathered over the years support the view that the earlier e-μ universality, i.e. the similarity in the properties of the e and μ, can be extended to e-μ–τ universality. The earlier enigma regarding the existence of muon is thus deepened. It now becomes the so-called 'generation puzzle': among the ultimate constituents of matter, why do members of one generation behave exactly in the same way, except for the mass, as the corresponding members of another generation?

As for the tau mass, recent measurements at the Beijing Electron Positron Collider (BEPC) in China, give $m_\tau = 1777$ MeV, with an error which is less than 1 MeV. The relatively large mass of tau implies that many final states are accessible for the tau decay. The availability of several possible channels for decay makes the tau a very shortlived particle. Its mean life is presently known to be about

$$\tau_\tau = 3 \times 10^{-13}\ \text{s},$$

with 1% accuracy, to be compared with

$$\tau_\mu = 2.197 \times 10^{-06}\ \text{s}.$$

Suggested Reading

C L Cowan Jr. , F Reines, F B Harrison, J W Kruse, A D McGuire. *Science*, 124:103-104. 1956.

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Bose-Einstein Condensation Observed

High-Tech Experiment Confirms Long-Standing Prediction

Rajaram Nityananda

Statistics is concerned with the laws which govern large collections of random events. Statistical ideas entered physics through the work by Maxwell and Boltzmann on the kinetic theory of gases, more than a century ago. For example, they predicted that the probability distribution of one component of the velocity would be the bell shaped curve in *Figure 1. Figures 1 a,b* shows how the spread in velocity, (or momentum) of particles, decreases as the temperature is lowered.

In 1924, Satyendra Nath Bose, then in Dacca University, discovered a new form of statistics, which applies to indistinguishable particles.