# Nobel leptons

This is the year of the leptons. Of the six leptons of today's particle physics, Nobel Prizes were awarded earlier for discovering two of them: the electron and the muon-neutrino. This year it is the turn of two more leptons, the electron-neutrino and the tau lepton, to acquire 'Nobelity'.

Frederick Reines (University of California, Irvine), aged 77, reported the first direct evidence for the existence of the 'neutrino' in 1956. He performed the experiments jointly with Clyde L. Cowan, Jr, who died in 1974. The neutrino is a tiny neutral particle hypothesized by Wolfgang Pauli, Jr. way back in 1930, and was thought to be unobservable. Twenty five years later and with the invention of the nuclear reactor it was possible to verify the neutrino hypothesis.

Martin Perl (Stanford University, Stanford), aged 68, assisted by a 35-member team, discovered the 'tau lepton' in 1975. This particle carries a unit of electric charge and weighs approximately twice as much as the proton. It is characterized by a short life of only a fraction of a pico-second and has the distiction of being the heaviest and the shortest-lived lepton. It is interesting that while Reines's neutrino results were long hoped for, Perl's tau discovery came as a complete surprise – that too at a time when people were busy establishing the charm flavour around the same mass. The tau lepton heralded the existence of the 'third generation' of fundamental constituents of matter.

## A brief history of the neutrino

The neutrino is the smallest bit of material reality ever conceived of by man, the largest is the universe. To attempt to understand something of one in terms of the other is to attempt to span the dimension in which lie all manifestations of natural law. Yet even now, despite our shadowy knowledge of these limits, problems arise to try the imagination in such an attempt.

F. Reines and C. L. Cowan, Jr.[1].

Neutrino 'was born' in a letter written by Pauli. This historic letter dated 4 December 1930 from Zürich, started with the unusual greeting 'Dear Radioactive Ladies and Gentlemen', and was read out at the Tübingen meeting. Pauli 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 letter referred to the hypothetical particle as 'the neutron' (the nuclear constituent neutron was discovered later by James Chadwick in 1932). In Italian the word 'neutrone' means something like 'large neutral one'. It was Enrico Fermi who named the Pauli particle as the 'neutrino', meaning the little neutral one, and that name stuck on.

In 1931 Pauli visited Rome and discussed his proposal of the particle with Fermi who received the idea with 'a very positive attitude'. Official announcement of the neutrino by Pauli was made at the Solvay conference in October 1933, as a particle which possessed 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.

It is interesting that even the great Pauli did not fully recognize the implications of the neutrino, particularly in regard to its penetrating power. His own account of this early period, written sometime in 1957, is extremely fascinating and is now available in English translation[2]. 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 (note 1).

It was Bruno Pontecorvo who first suggested that the process of inverse beta decay could be used as a way to establishing the neutrino. In 1946 he proposed the celebrated Chlorine–Argon radiochemical method and suggested using the source of reactor neutrinos[2] for the experiment. The Cl–Ar method was taken up almost as a life-long project by the solar-neutrino pioneer Raymond Davis, Jr. (note 2).

## Detection of the reactor neutrino

The first neutrino reaction observed (note 3) was the inverse nuclear beta reaction

$$\bar{\nu}_e + p \rightarrow e^+ + n, \qquad (1)$$

driven by the antineutrinos from the nuclear reactor. This reaction is essentially the reverse of the neutron decay $n \rightarrow p + e^- + \bar{\nu}_e$ from which it is obtainable by transposing the $e^-$ to the left hand side as a $e^+$ and reversing the reaction arrow. The energy of the incident antineutrino could be deduced from the positron momentum:

$$E_{\bar{\nu}_e} = \frac{E_e + \Delta + [(\Delta^2 - m_e^2)/2M_p]}{1 - [(E_e - p_e\cos\theta)/M_p]} \qquad (2)$$

$$\simeq E_e + \Delta \qquad (3)$$

$$\geq 1.804 \text{ MeV}, \qquad (4)$$

where $E_e$ is the positron energy, $p_e$ is the magnitude of its 3-momentum, $\theta$ is the positron emission angle with respect to the antineutrino direction, and $\Delta = M_n - M_p = 1.293$ MeV is the neutron–proton mass difference; the second step ignores neutron recoil terms of order $(E_e/M_p)$ and the last one gives the reaction threshold.

For MeV range of antineutrino energies, the positron angular distribution is nearly isotropic ($\langle\cos\theta\rangle = -0.04$) and the effective cross section may be taken to be (note 4)

$$\sigma = \frac{4G_F^2}{\pi} p_e E_e, \qquad (5)$$

where $G_F$ is the Fermi coupling constant; for $E_{\nu_e} = 2.3$ MeV the cross section is

$$\sigma \simeq 6\times10^{-44} \text{ cm}^2. \qquad (6)$$

The idea underlying the Nobel Prize-winning experiment 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[3] was performed around 1955–56. The projectiles were the reactor neutrinos from the Savannah River Plant located 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 could be viewed as a multiple-sandwich with 2 layers of cheese (target material) arranged between 3 pieces of

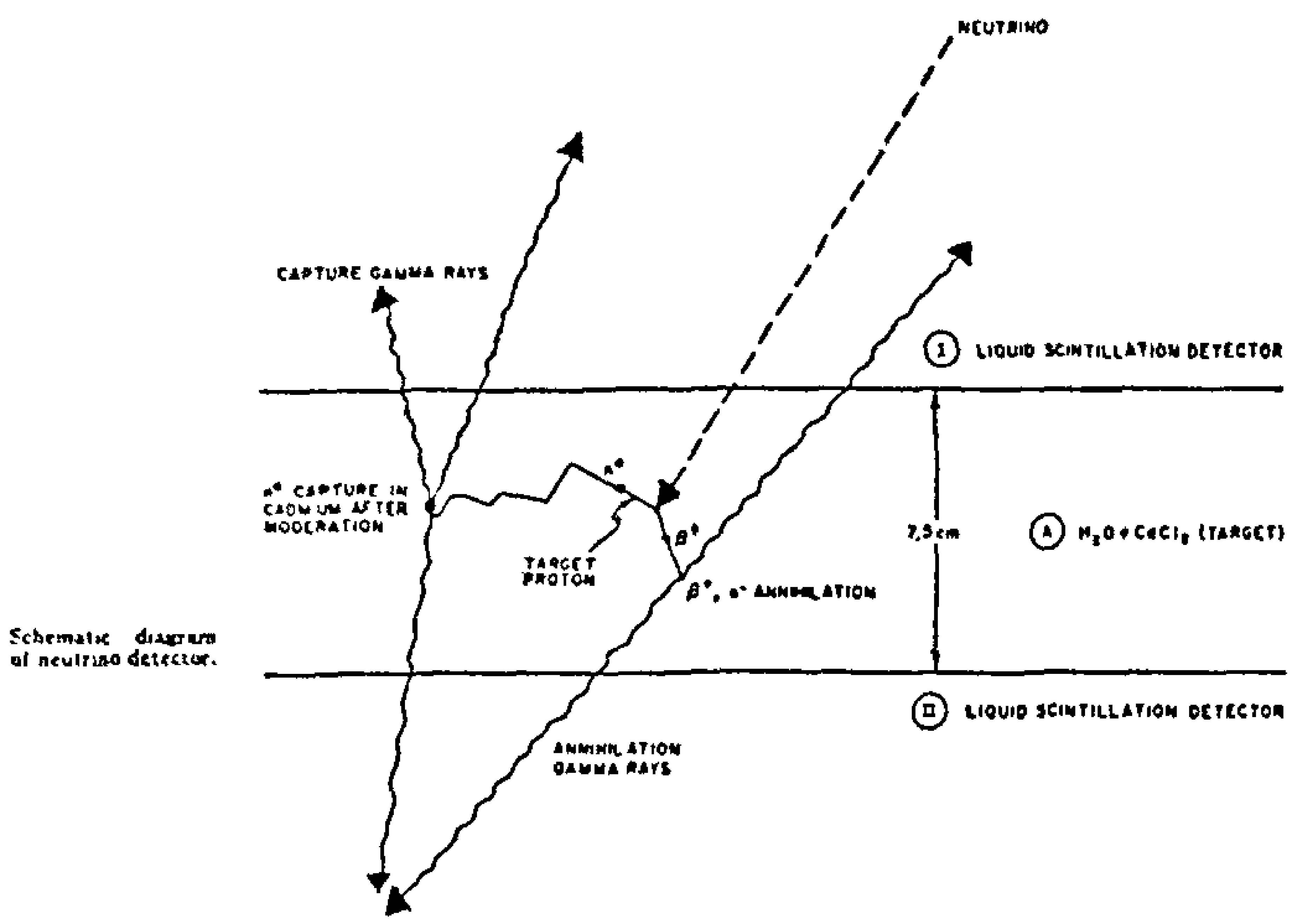


**Figure 1.** Schematic diagram of the neutrino detector of Reines–Cowan experiment[4].

bread: the cheese layers were the two target tanks containing a solution of water and $CdCl_2$, while the bread pieces were the three liquid scintillator detectors.

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 prompt coincidence was due to the capture of neutron by cadmium giving a few photons (with total energy of 9 MeV). The second pulse occurred after several micro-seconds of the positron flash, the time it took for the neutron to be thermalized in the target water. The experiment involved, among other things, measuring the energies of the pulses, their time-delays, dependence of event rate with neutrino flux which varied with the reactor power output, etc.

The results were published in the 5-author paper C. L. Cowan, Jr. *et al.*[3] entitled 'Detection of the Free Neutrino: A Confirmation'. This paper, unusual for the lack of diagrams of the detector or the customary figures or tables, is regarded as the discovery paper (note 5). Photographs of the detector assembly and associated equipment can be seen in ref. 4. The observed signal varied with the reactor-power. It consisted of an average rate of $2.88 \pm 0.22$ counts/hour, consistent with a value $\sim 6 \times 10^{-44}\,\text{cm}^2$ for the inverse beta-reaction cross section. The signal to reactor-unrelated background ratio was 3 to 1.

It is remarkable that in the same year Reines and Cowan[1] also gave an upper limit on the neutrino magnetic moment,

$$\mu_{\bar{\nu}_e} < 10^{-9}\,\mu_B,$$

where $\mu_B$ is the Bohr magneton. This limit was deduced from the extent of non-observation of scintillator pulses along the path of the reactor neutrino, and is about the same as the present upper limit which is extracted by using different considerations (for a survey of the recent results in neutrino physics, see e.g., ref. 5).

Even today, we do not know very much about the electron-neutrino (and much less about other neutrinos). As for its mass, data on the end-point of the beta electron spectra only show that it does not exceed a few eV; a recent high statistics experiment[6] using molecular tritium in gaseous form, gave the upper limit

$$m(\bar{\nu}_e) < 4.35\ \text{eV}, \tag{7}$$

at 95% confidence level.

Experimental data with $\nu_e$s are not extensive because it is difficult to obtain $\nu_e$ beams. At the pi-meson factories, low energy $\nu_e$ get produced in 3-body decays and along with muon-neutrinos ($\nu_\mu$ and $\bar{\nu}_\mu$). Sun is no doubt a good source of $\nu_e$ but solar neutrino fluxes are not well understood and constitute one of the challenging problems of current research. Only recently the first experiment using a man-made source of pure $\nu_e$ was performed. It made use of an intense source of reactor-produced $^{51}Cr$ (which emits $\nu_e$ by electron capture) to calibrate the GALLEX solar neutrino detector[7].

## Discovery of the tau lepton

The tau lepton broke on the scene unexpectedly. While the results of Reines needed the construction of power reactors, the discovery of 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 $\tau$ is the first in the word triton, meaning third). Its birth can be traced to the 1975 paper entitled, 'Evidence for anomalous lepton production in $e^+ - e^-$ annihilation' by Perl *et al.*[8].

The experiment was performed at the electron–positron collider called SPEAR (Stanford Positron Electron Accelerator Ring). At this facility, 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)

$$E_{cm} = E_{e^-} + E_{e^+} \tag{8}$$

$$= 2E_{e^-}, \tag{9}$$

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.

A large cylindrical detector placed in a magnetic field surrounded the collision area. Electrons were identified by the electromagnetic shower counters, and muons by their ability to penetrate large amounts of iron and other materials making up a total of 1.7 absorption lengths for pions. Particles emitted at polar angles between 50° and 130° and at all azimuthal angles were recorded.

*Anomalous events.* The 'anomalous' events reported by Perl and collaborators corresponded to the following reactions which had a very distinctive signature,

$$e^- + e^+ \rightarrow e^- + \mu^+ + \text{i.p.}, \tag{10}$$

$$\rightarrow e^+ + \mu^- + \text{i.p.}, \tag{11}$$

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 arose from the separate decays of two new particles which were oppositely-charged and short-lived. In an effort to reduce the background due to the copious production of $e^+e^-$ and $\mu^+\mu^-$ pairs, the events were chosen to be 'acoplanar' so that production of more than two particles was ensured. For this the $\mu$ was required to make an angle more than 20° to the plane that contained the final e and the incident beam.

The very first report of Perl *et al.*[8] had a total of 64 anomalous events at the SPEAR range of energies. For example, at the energy $E_{cm} = 4.8$ GeV there were 24 events (13 $e^+\mu^-$ and 11 $e^-\mu^+$) with an estimated background consisting of about 5 events (arising from possible misidentification of hadrons as leptons, decays of known hadrons into leptons, etc). The events were found to be 'noncollinear', meaning that the angle between the e and $\mu$ momenta was more than 90° and the two particles were emitted in opposite hemispheres with respect to the beam.

*Threshold behaviour.* The occurrence of anomalous events as a function of $E_{cm}$ exhibited an increase around 4 GeV, as shown in Figure 2. This indicated the existence of a threshold for the production of anomalous events. Moreover, in producing a pair of point-particles $\tau^+\tau^-$ by one-photon exchange

$$e^+ + e^- \rightarrow \gamma_{virtual} \rightarrow \tau^+ + \tau^-, \qquad (12)$$

quantum electrodynamics tells us that the total cross section $\sigma_{\tau\tau}$ should depend on the final velocity $\beta$ as follows:

$$\sigma_{\tau\tau} = \frac{(3-\beta^2)}{2}\beta\sigma_0 \quad (\text{for spin } \tfrac{1}{2}), \qquad (13)$$

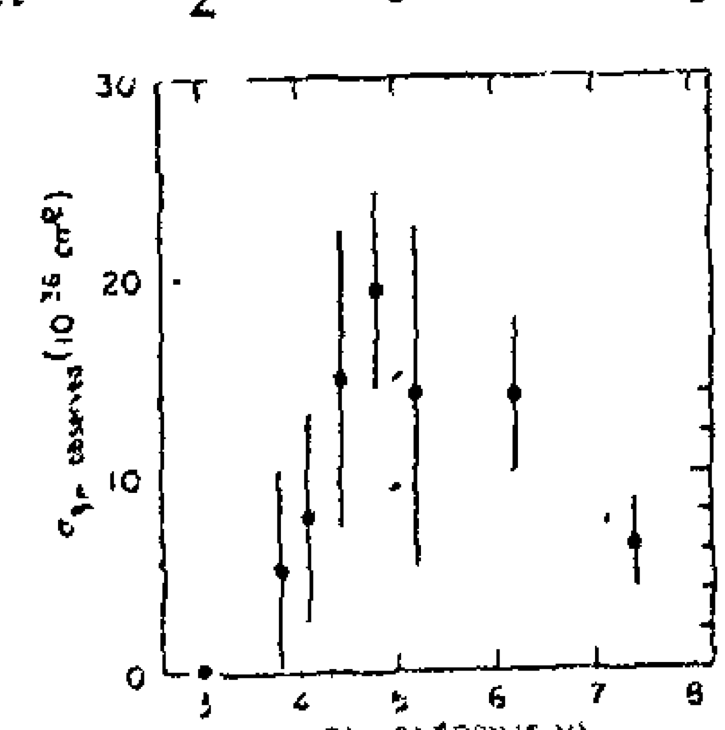

**Figure 2.** The observed cross section for the anomalous e–$\mu$ events[8].

$$= \frac{\beta^3}{4}\sigma_0 \quad (\text{for spin } 0), \qquad (14)$$

where

$$\beta = \sqrt{1 - \frac{4M_\tau^2}{E_{cm}^2}}; \; \sigma_0 \equiv \frac{4\pi\alpha^2}{3E_{cm}^2}; \; \alpha \simeq \frac{1}{137}. \qquad (15)$$

In the boson case, the $\beta^3$ dependence arises from the p-wave production which is a result of parity conservation in electromagnetic interactions. Subsequent experimental observations were consistent with a linear rise of the cross section with velocity and thus for the $\tau^\pm$ the assignment of spin $\frac{1}{2}$ was preferred over spin 0 and other possibilities.

Final interpretation of the anomalous events followed soon[9]: electron–positron annihilation gives rise to a pair of tau leptons

$$e^+ + e^- \rightarrow \tau^- + \tau^+ \qquad (16)$$

which decay immediately into lighter leptons. The 'tau–lepton number' conservation is respected by assuming the emission of an associated neutrino called the tau-neutrino ($\nu_\tau$) in the $\tau^-$ decay, and a tau-antineutrino ($\bar{\nu}_\tau$) in the $\tau^+$ decay. Thus to explain the anomalous event with, say, $e^-\mu^+$ we should appeal to the decays

$$\tau^- \rightarrow e^- + \bar{\nu}_e + \nu_\tau, \qquad (17)$$

$$\tau^+ \rightarrow \mu^+ + \nu_\mu + \bar{\nu}_\tau, \qquad (18)$$

wherein the two neutrinos and the two antineutrinos (belonging to all three neutrino generations) constitute the invisible particles.

Data gathered over the years have shown that the shape of the electron (and also muon) energy spectrum in tau decay is in good agreement[10] with the standard V–A theory. Also all the observations support the view that the e–$\mu$ universality is extendible to e–$\mu$–$\tau$ universality. Thus the original enigma regarding the existence of muon is 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 mass, as the corresponding members of another generation?

It may be interesting to recall that in 1974 the spectacular discovery of $J/\psi$ (3.097 GeV) immediately brought forth in its wake an intense frenzy of activity relating to the charm flavour. People were busy studying the spectroscopy of hidden-charm states and open-charm states and their decays. Consequently the feeling prevalent at the time was that Perl's anomalous events were some obscure manifestation of charm decays and the situation would be clearing up soon. However such feelings were firmly dispelled by 1977 when the Double Arm Spectrometer (DASP) group[11] working at DESY, Germany, reported seeing the anomalous $e\mu$ events around $\psi'$ (3.686 GeV) manifestly below the open-charm threshold (2 × 1.87 GeV).

The present best value for the tau lepton mass comes from the measurements at the Beijing Electron Positron Collider (BEPC)[12], and is given by

$$m_\tau = 1776.96^{+0.18+0.25}_{-0.21-0.17}\ \text{MeV}, \qquad (19)$$

where the first error is statistical and the second systematic. The relatively large mass of the tau implies a large phase space for decay, and this makes a variety of final states to be accessible for the tau decay. Some of the decay states contain 5 charged particles (pions or kaons) besides the missing tau-neutrino and possibly one or two neutral pions. The availability of several competing channels for decay (e.g., the relative decay probability for $\tau^- \rightarrow \pi^- + \nu_\tau$ is (11.7 ± 0.4)%), makes the tau a very shortlived particle. Its meanlife is presently known to 1% accuracy[13],

$$\tau_\tau = (2.956 \pm 0.031) \times 10^{-13}\ \text{s}. \qquad (20)$$

Finally, in regard to the mass of the tau-neutrino, the information available is very limited: the mass limit obtained from a recent study[14] of the tau-decay events each containing 5 charged pions is, $m(\nu_\tau) < 24$ MeV at 95% confidence level.

## Summary

The announcement of this year's Nobel award in Physics is in recognition of two landmark experiments in elementary particle physics. One provided the first confirmation of the neutrino, as envisaged by Pauli more than two decades earlier, as a tiny neutral particle emitted in beta decay. The experiment made an ingenious use of time-correlations of scintillator pulses to ascertain the occurrence of the inverse scattering reaction.

Table 1. Lepton generations

| Generation | Lepton | Discoverer(s) (year) | Nobel Prize winner(s) (year) |
|---|---|---|---|
| 1 | electron, e | J. J. Thomson (1897) | J. J. Thomson (1906) |
| | electron-neutrino $\nu_e$ | C. L. Cowan *et al.*[3] (1956) | F. J. Reines (1995) |
| 2 | muon $\mu$ | J. C. Street, E. C. Stevenson; C. D. Anderson, S. H. Neddermeyer (1936) | – |
| | muon-neutrino $\nu_\mu$ | G. Danby *et al.*[16] (1962) | M. Schwartz, L. M. Lederman, J. Steinberger (1988) |
| 3 | tau $\tau$ | M. L. Perl *et al.*[8] (1975) | M. L. Perl (1995) |
| | tau-neutrino $\nu_\tau$ | ? | ? |

The other experimental investigation which shared this year's honour is the discovery of the heavy charged lepton $\tau$. This was a serendipitous discovery perhaps like that of the muon. The 'anomalous' events with the oppositely-charged e and $\mu$ were interpreted as resulting from the independent decays of the shortlived pair $\tau^+\tau^-$ which was created in the reaction $e^+ + e^- \rightarrow \tau^+ + \tau^-$ The $\tau$ is a member of the third (and perhaps the last) generation of ultimate constituents of matter to which the top and bottom quarks belong (see e.g. ref. 15).

A summary of the discoveries made in the world of leptons is given in Table 1. We see that the third generation has started getting Nobel prizes. It is amusing that the charged-leptons crop up with a 39-year gap and may be the 4th one would show up in the year 2114. For the present, the available experimental information implies that there are no charged leptons which are heavier than the tau and lighter than 45 GeV.

Finally it should be emphasized that the third kind of neutrino $\nu_\tau$ still needs to be identified experimentally (this is shown by question marks). To this end one ought to demonstrate that $\tau$s are produced directly in collisions of the $\nu_\tau$ with nuclear targets. However $\nu_\tau$ beams are hard to obtain mainly due to the short intrinsic lifetime of the $\tau$.


1. Reines, F. and Cowan, Jr., C. L., *Nature*, 1956, **178**, 446–449.
2. Pauli, W., in *Neutrino Physics* (ed. Winter, K), Cambridge University Press, 1991, pp. 1–25.
3. Cowan, Jr., C. L., Reines, F., Harrison, F. B., Kruse, H. W. and McGuire, A. D., *Science*, 1956, **124**, 103–104.
4. Reines, F. and Cowan, Jr., C. L., *Phys. Today*, 1957, **10**, 12–18.
5. Sarma, K. V. L., *Int. J. Mod. Phys.*, 1995, **A10**, 767–783.
6. Belesev, A. I. *et al.*, *Phys. Lett.*, 1995, **B350**, 263–272.
7. Anselmann, P. *et al.*, *Phys. Lett.*, 1995, **B342**, 440–450.
8. Perl, M. L. *et al.*, *Phys. Rev. Lett.*, 1975, **35**, 1489–1492.
9. Perl, M. L. *et al.*, *Phys. Lett.*, 1976, **B63**, 466–470.
10. Perl, M. L. *et al.*, *Phys. Lett.*, 1977, **B70**, 487–490.
11. Brandelik, R. *et al.*, *Phys. Lett.*, 1978, **B73**, 109–114.
12. Bai, J. Z. *et al.*, SLAC-PUB-95-6930, BIHEP-EPI-95-004, July 1995, (submitted to *Phys. Rev. D*).
13. Montanet, L. *et al.*, *Phys. Rev.*, 1994, **D50**, 1173–1827.
14. Buskulic, D. *et al.* (ALEPH Collaboration), *Phys. Lett.*, 1995, **B349**, 585–596.
15. Sarma, K. V. L., *Curr. Sci.*, 1995, **68**, 605–611.
16. Danby, G. *et al.*, *Phys. Rev. Lett.*, 1962, **9**, 36–44.


## Notes

1. For the case of reactor antineutrinos going through water, taking the cross section to be $\sigma(\bar{\nu}_e + p \rightarrow e^+ + n) \sim 6 \times 10^{-44}$ cm$^2$ and noting that there are two free proton targets per water molecule, the interaction mean free path will be $\lambda = (1/n\sigma) \simeq 2.5 \times 10^{20}$ cm $\simeq 260$ light years!
2. It is worth recalling that the Cl–Ar experiment of Davis performed in 1956 at the Savannah River Plant reactor was a 'failure'. The result was not clearly inconsistent with background. The null result $\sigma$(reactor $\nu + {}^{37}Cl \rightarrow e^- + {}^{37}Ar$) $< 0.9 \times 10^{-45}$ cm$^2$ was interpreted to demonstrate that the reactor neutrino is not $\nu_e$ but $\bar{\nu}_e$. Since $\bar{\nu}_e$'s are emitted in the beta decays of neutrons and neutron-rich nuclei, a fission reactor is an abundant source of $\bar{\nu}_e$.
3. Here as is customary the word 'neutrino' is being used in its generic sense although, strictly speaking, what Reines and his group detected were the signals from the electron-antineutrino $\bar{\nu}_e$.
4. At MeV energies this has an approximate quadratic dependence on the incident neutrino energy $E_\nu$; at higher energies (above GeV) it becomes independent of $E_\nu$ due to the rapid decrease of the vector and axial-vector form factors. However the total cross section increases linearly with $E_\nu$, as a consequence of the point nature of the target quark. At still higher energies (where the $W$ mass effects become important) the total cross section is expected to increase logarithmically, as is indicated in the recent HERA experiments ep $\rightarrow \nu_e + \ldots$ .
5. The earlier 1953 experiment of Reines and Cowan, *Phys. Rev.*, 1953, **90**, 492; **92**, 830) performed at the Hanford reactor in Washington, did not give a signal well above the background that was unrelated to the reactor. The number of delayed coincidences had a large uncertainty, 0.41 ± 0.20 per hour.

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