
What's old and what's new about neutrinos

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To save the laws of conservation of energy, linear and angular momentum, Pauli suggested the possible existence of an elementary particle possessing no electric charge and very little mass called the neutrino, which was emitted in β -decay of the nuclei. Subsequent work over the decades has proved the existence of this particle and has proved its importance not only to the physics of elementary particles but also to astrophysics and cosmology. This article is triggered by the recent experiments which show that the neutrinos of one flavour, as they speed through space, periodically transmogrify onto other flavours. This discovery is comparable to the discovery of the electron in that it provides the basis to new physics beyond the currently accepted Standard Model.

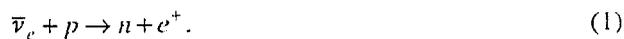
CONSIDERABLE excitement amongst physicists and astronomers was recently sparked off by the announcement of the confirmation of neutrino oscillations by the Super-Kamiokande collaboration at the XVII Interna-

tional Conference of Neutrino Physics and Astrophysics held in Takayama, Japan early this June. For, the oscillations imply that the neutrino, hitherto regarded as being massless in the Standard Model of the particle physics, has a finite rest mass. Thus, in a dramatic reversal of roles the tiny neutrino may indeed dominate the gravitational dynamics of the whole Universe.

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According to T. Kajita who presented the data and analysis on atmospheric neutrinos, there is a deficit of about 50% in the flux of muon neutrinos as seen by their underground detector. By studying the zenith angle distribution of muons induced by neutrinos it was concluded that this deficit in all likelihood was caused by the $\nu_\mu \leftrightarrow \nu_\tau$ oscillations with $\Delta m^2 \equiv (m_\tau^2 - m_\mu^2)$ of 10^{-3} to 10^{-2} eV². Such a value of Δm^2 implies a lower bound on the mass of one of the neutrinos of $m_\nu > \sqrt{\Delta m^2} \approx 10^{-1}$ eV. This is an important signal of the new physics beyond the Standard Model. It is interesting to note that even at this lower bound, the neutrinos produced in the big bang would contribute on average as much to the mean density of the universe as all the stars and other visible matter in all the galaxies put together. To the cognoscenti nothing more need be said. To others, however, a road-map with important milestones of development may be of interest¹.

Neutrino as a neutral particle with a tiny mass but no electric charge was originally suggested by Pauli in 1930, to explain the apparent nonconservation of energy and angular momentum in β -decay. The key events in our understanding of the neutrino and its importance in physics and cosmology are listed in Table 1. Despite the success of the Fermi theory in explaining the β -decay life times and spectra, surprisingly (from today's vantage point) the neutrino as an elementary particle was still treated with some degree of suspicion until 1956, when Reines, Cowan and others actually 'saw' the neutrino (in fact the antineutrino that is emitted when a neutron decays) induce the inverse β -decay as shown in the reaction below



The end products of this reaction, the neutron and the positron are of course easily observed by suitable particle detectors. But, they were observed in 'coincidence' so that even though the reaction cross-section was extremely small $\sim 10^{-44}$ cm², it was possible to identify the reaction unambiguously. The ideas of parity-nonconservation (absence of mirror symmetry), the V-A theory incorporating such a nonconservation (by Sudarshan amongst others) and the experimental confirmation of parity violation all followed within about a year.

Developments in neutrino physics after this initial period became many faceted and beautiful with the ideas of gauge invariance driving the theory to electro-weak unification and with magnificent experiments confirming and occasionally extending the theoretical concepts. It would be impossible to trace these wonderful developments here but it is noteworthy that these ideas coupled with parallel ideas in the theory of strong interactions led to the 'Standard Model' of particle physics.

Table 1a. History of the neutrino

1896	Becquerel discovers radioactivity
1906	Experiments of β -ray spectra begin
1914	Continuous energy spectrum of β -rays confirmed
1928	Quantum statistics
1929	Bohr considers energy nonconservation in β -decay
1930	Pauli enunciates the neutrino hypothesis
1933	Fermi-theory of β -decay
1935	Meyer and Wigner estimate double β -decay life time
1937	Yukawa theory of nuclear forces
1937	Bhabha shows that Yukawa particle will β -decay
1938	Bhabha predicts a new particle - (the muon)
1956	Reines and Cowan 'see' neutrino interactions
1957	Lee and Yang propose parity nonconservation Idea of left-handed neutrino and V-A theory proposed.

Table 1b. Some recent developments

1962	Lederman, Schwartz and Steinberger show that ν_μ makes only muons, indicating $\nu_\mu \neq \nu_e$; Bhabha's prediction is borne out.
1963	Cowsik <i>et al.</i> calculate fluxes of $\nu_\mu, \bar{\nu}_\mu, \nu_e, \bar{\nu}_e$, generated by cosmic rays in the earth's atmosphere, including the contribution of K-decay.
1964	Cowsik, Yash Pal and Tandon discuss effects of a degenerate sea of neutrinos filling the universe.
1965	TIFR and Irvine-Witswaterstrand collaboration see cosmic ray neutrino-induced muons.
1966	Gerstein and Zeidovich set an upper bound on $m_{\nu\mu}$ from cosmological considerations.
1968	Kirsten <i>et al.</i> measure the $\beta\beta$ -decay life time of ¹³⁰ Te.
1969	Schvarzman on the basis of cosmological He abundance, places an upper bound on the number of 'difficult to observe particles' like neutrinos.
1972	Cowsik and McClelland set an upper bound $\sum m_{\nu_i} + m_{bi} < 90 h^2$ eV.
1972	Cowsik and McClelland propose that weakly-interacting particles like neutrinos with finite rest mass will dominate the gravitational dynamics of the universe and will trigger the formation of galaxies and generically form halos of dark matter around galactic systems.
1975-76	Perl discovers the τ lepton.
1977	Steigman, Schramm and Gunn set an upper bound of 4-lepton families, based on Schwartsman's idea.
1977	Cowsik sets stringent limits on the radiative decay of the neutrino.
1980's	Volkova, Gaisser improve calculations of atmospheric flux calculations.
1990	LEP collider measures Z^0 width and confirm that there are only 3 'active' neutrinos.
1992	Cowsik-Washington University collaboration measures precisely the $\beta\beta$ -decay life times tellurium isotopes ¹²⁸ $\tau = 7.7 \times 10^{24}$ yr and ¹³⁰ $\tau = 2-7 \times 10^{21}$ yr leading to $\langle m_{\nu_i} \rangle_{Majorana} < 1$ eV.
1970-1998	Many international groups establish the energy-dependent depletion in the solar neutrino flux.
1992	Kamiokande announces depletion in the flux of atmospheric muon neutrinos.
1998	Super-Kamiokande quantifies the depletion in atmospheric ν_μ flux and $\nu_\mu \leftrightarrow \nu_\tau$ oscillation confirmed with $\Delta m^2 \sim 10^{-2}-10^{-3}$ eV ² .

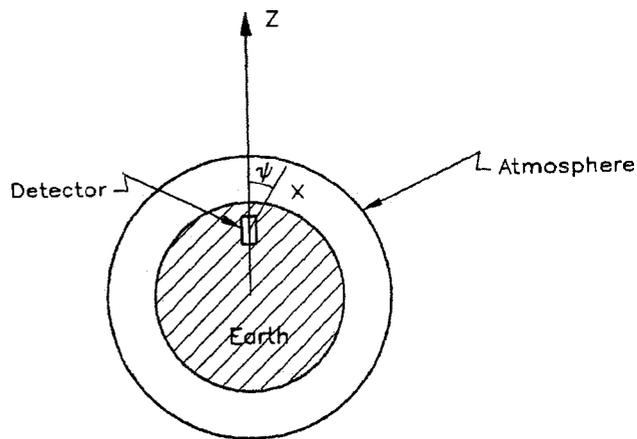


Figure 1. Neutrinos are produced by cosmic rays as they traverse the first couple of 100 gcm^{-2} of the earth's atmosphere. The distance x the neutrinos have to travel before they enter the Kamiokande detector increases with the zenith angle ψ .

To appreciate the recent findings of the Super-Kamiokande group, it will do well to recall that within the Standard Model neutrinos are treated as being massless even though no fundamental ideas of symmetry prescribe this choice. Secondly, both the theoretical studies of cosmological synthesis of helium and the experimental measurements of the width of the weak intermediate boson Z^0 indicate that there are only 3 generations of neutrinos, ν_e , ν_μ and ν_τ , which have the standard couplings of weak interactions. Any other neutrino that one may ponder about must have a much smaller coupling or be 'inert'.

Now we are almost ready with the theoretical framework to understand the results of the Japanese experiment which imply that neutrinos have a finite rest mass. Let us assume that there are 3 neutrinos ν_1, ν_2, ν_3 with masses m_1, m_2 and m_3 . Since we can have three and only three active neutrinos, how do we accommodate the additional ν_e, ν_μ and ν_τ flavour which have all been detected? As pointed out by Pontecarvo back in 1957, we may think of ν_1, ν_2 and ν_3 as being linear superposition of ν_e, ν_μ and ν_τ . Accordingly, we may write,

$$\begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} = U \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} \quad \text{or} \quad \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U^+ \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}, \quad (2)$$

where U is the mixing matrix which has to be unitary, of course. As implied by eq. (2) above, the flavour eigenstates which tell us the kind of leptons (e, μ, τ) which the neutrinos can produce in interactions, are not the mass eigenstates which tell us how rapidly the phase of wave function changes during propagation.

The qualitative aspects of mixing of different neutrino flavours may be illustrated by an example. Consider the

situation when only two of the neutrinos, say ν_μ and ν_τ are involved. Thus,

$$\begin{aligned} |\nu_\mu\rangle &= \cos\theta |\nu_1\rangle + \sin\theta |\nu_2\rangle, \\ |\nu_\tau\rangle &= -\sin\theta |\nu_1\rangle + \cos\theta |\nu_2\rangle, \end{aligned} \quad (3)$$

where θ is called the mixing angle. When ν_μ is produced, say in π -decay ($\pi^- \rightarrow \nu_\mu + \mu^-$) then to start with, the relative phases of $|\nu_1\rangle$ and $|\nu_2\rangle$ are fixed to be zero, say. But as time evolves, the phase of $|\nu_2\rangle$ evolves more rapidly since m_2 is assumed to be larger than m_1 . This leads to an interference between ν_μ and ν_τ , and the probability of seeing a ν_μ of momentum p after it has traversed a distance x can be shown to be given by,

$$P(\nu_\mu, \nu_\mu, x) = 1 - 2\sin^2 2\theta \sin^2(\Delta m^2 x / 4p_\nu), \quad (4)$$

where it is assumed that $p_\nu \gg m_1$ or m_2 ; $\Delta m^2 \equiv m_1^2 - m_2^2$ and $\hbar = c = 1$ units are adopted. Since the total probability has to be unity, the disappearance of the μ_ν will reappear as a finite flux of μ_τ .

The experiments at Kamiokande were designed to measure this probability P as a function of x and thereby measure θ and Δm^2 , the crucial parameters that describe neutrino mixing. The source of neutrinos in the Kamiokande experiments is the decay of π^\pm and K^\pm , and K^0 generated by the interactions of cosmic rays in the earth's atmosphere²⁻⁸. There is competition between decay and secondary interactions of the pions and the kaons, both of which tend to decrease flux of π^\pm and K^\pm , and K^0 . At lower energies, the decay dominates and neutrinos and antineutrinos, mostly of muon and electron flavours, are generated. The neutrino flux and angular distribution thus generated by cosmic rays have been calculated with progressively increasing accuracy and detail by various authors²⁻⁸. Figure 1 shows clearly that as the zenith angle ψ increases, so does the path length x that the neutrinos have to traverse before being detected by a neutrino detector placed deep underground (for example, 1000 m underground at Kamiokande).

The super-Kamiokande detector is a huge cylinder, with typical dimensions of ~ 40 m, containing about 60 million litres of water. The walls of the cylinder as well as its top and bottom surfaces are all covered with about 10,000 photomultipliers each of area about 0.1 m^2 . Whenever a relativistic charged particle passes through this detector, it will generate a cone of Cerenkov light which is imaged by these photomultipliers which, in combination, function like a fly's eye. From the pulse heights in the various photomultipliers, one may deduce the direction, energy and the mass of the charged particle produced by the neutrinos in the water (if their energy is below a few GeV). The neutrinos interact with the proton and oxygen nuclei as well as with the electrons through neutral and charged current weak interactions (see Figure 2).

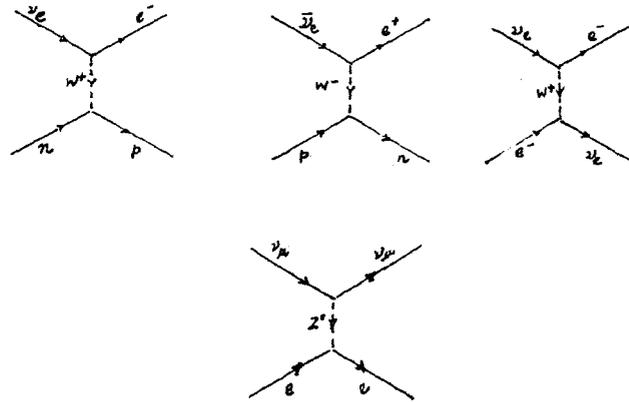


Figure 2. Three examples of scattering through charged currents (upper row) and one example of scattering through neutral current (lower row) are shown; note that they are distinguished by the charge or neutrality of the exchange particle W^\pm or Z^0 respectively.

The production of μ^- and μ^+ in the detector by cosmic ray generated ν_μ and $\bar{\nu}_\mu$ (occasionally accompanied with π^+ , π^- , etc.) is the signal that allows the experimenter to measure the flux and the angular distribution of these neutrinos, since the interaction cross section for these processes has already been well determined at the particle accelerators in Geneva, Brookhaven and Chicago. Nearly two years of data acquired with the super-Kamiokande detector showed that the 'observed' fluxes of ν_μ and $\bar{\nu}_\mu$ were substantially smaller than the theoretically-calculated fluxes! Furthermore, the deviations tended to be more at larger zenith angles where the neutrinos have to travel a greater distance x , from the point of production to the point of detection. To reduce the effect of the uncertainties in theoretical calculations, the super-Kamiokande group quotes in two energy intervals the ratios of observed fluxes of muons to that of electrons as being:

$$R \equiv \frac{(\mu/e)_{\text{observed}}}{(\mu/e)_{\text{theory}}} = 0.63^{+0.0026}_{-0.0025}(\text{stat}) \pm 0.05(\text{sys})(\text{sub GeV})$$

$$= 0.65 \pm 0.05(\text{stat}) \pm 0.08(\text{multi GeV}). \quad (5)$$

This reduction in the flux and its zenith angle dependence have been analysed by the authors in terms of the $\nu_\mu \leftrightarrow \nu_\tau$ oscillations given in eq. (4). The central values of $\sin^2 2\theta$ and Δm^2 obtained by them are given below:

$$\sin^2 2\theta \sim 1; (m_1^2 - m_2^2) \equiv \Delta m^2 \approx 5 \times 10^{-3} \text{ eV}^2. \quad (6)$$

Box 1

What we have described thus far, is the phenomenon of neutrino oscillations in vacuum. Additional effects are expected when neutrinos traverse matter as suggested by Wolfenstein and worked out in detail by Mikhaev and Smirnov. The effect is not unlike propagation of an optical wave front through a birefringent medium. Whereas all the neutrinos can interact through neutral currents with nuclei and electrons with equal strength, it is only the electron neutrinos that have the additional charge-current interaction with the electrons of the medium. The additional phase shift that the electron neutrinos suffer in a medium can be described in terms of an effective refractive index $n_{cc} = 1 + \sqrt{2}G_F N_e / p$, where G_F is the Fermi coupling constant, N_e is the number density of the electrons and p is the neutrino momentum. This causes an interference between ν_e and ν_μ , which can become totally destructive or constructive depending on the distance. Thus, for example, for a suitable choice of the mixing parameters and momenta the ν_e traversing the dense core of the sun may be transformed into ν_μ . The energy-dependent suppression in the flux of the solar neutrinos through such a process is called the MSW effect.

There is considerable uncertainty in the precise value of Δm^2 and we may expect that in about five years the underground experiments at Kamiokande and others being carried out elsewhere will be able to pin it down to within a factor of about 2.

There is another result from super-Kamiokande which is also of interest here; the deficit in flux of electron

Box 2

Any story of the neutrino will be incomplete without a mention of *neutrinoless* double beta decay. (For example, the decay $^{128}_{52}\text{Te} \rightarrow ^{128}_{54}\text{Xe} + 2\beta^-$ may occur without the emission of any neutrinos if lepton number conservation is violated.) The rate of such a process is proportional to the square of the Majorana mass of the electron neutrino $\langle m_{\nu_e} \rangle_{\text{Majorana}}$ defined by

$$\langle m_{\nu_e} \rangle_{\text{Majorana}} = \sum \eta_i U_{ie}^2 m_i.$$

The experiments of Cowsik and others from the Washington University⁹ which measured the $\beta\beta$ -decay life time of ^{128}Te to ^{128}Xe to be $\tau = 7.7 \times 10^{24}$ years (the longest life time ever to be measured) set an upper bound

$$\langle m_{\nu_e} \rangle_{\text{Majorana}} \leq 1 \text{ eV}.$$

This sets a stringent upper bound on any lepton number nonconservation and also constrains the elements of the mixing matrix U .

neutrinos from the Sun was confirmed and the energy dependence of the deficit was measured. However the deficit did not show any 'day-night' effect, indicating that passage of neutrinos through the dense core of the earth did not have a significant effect. For these and other reasons some doubts have been cast about the correctness of the matter-induced oscillation (see Box 1) being the cause for the deficit in the solar neutrino flux.

To test if $\nu_e \leftrightarrow \nu_\mu$ oscillation is indeed the correct explanation, Raju Raghavan (TIFR, now at Bell Labs) has suggested that we should observe the neutral current events in which both ν_μ and ν_e scatter the electrons in a detector along with the charged current events by ν_e generating electrons in a detector with a low energy threshold. Even though the apparent flux of ν_e may be depleted, if the oscillation to ν_μ is the cause of this reduction, the sum of the fluxes of ν_μ and ν_e should not be altered! Apart from this, the low energy threshold of the Borexino detector suggested by him will allow us to study the spectra of neutrinos accurately.

To return to the oscillations of the atmosphere cosmic-ray neutrinos, the value of $\Delta m^2 \sim 5 \times 10^{-3} \text{ eV}^2$, implies a lower bound on m_1 of $\sqrt{\Delta m^2} \sim 10^{-1} \text{ eV}$. Neutrinos with whatever mass, however small, herald the physics beyond the standard model of particle physics! This is the first time that a *lower bound* has been placed on the mass of the neutrino (see Box 2). In this note we have described the neutrino oscillations assuming the participation of only the two neutrinos ν_μ and ν_τ . A general analysis assuming that all three neutrinos are involved has been performed by Narayan *et al.*¹³.

Box 3

Any discussion of early history of particle physics must include references to the seminal contributions of Homi Jehangir Bhabha. He presented a relativistically invariant theory of β -decay which reduced to Fermi theory in the low energy limit (*Nature*, 1938, **141**, 117). On the basis of this theory he showed that the Yukawa particle, whose exchange is responsible for nuclear forces, will β -decay and thus cannot be the penetrating component seen in the cosmic rays. Discussing the penetrating component of cosmic rays, he states that it 'does not consist of electrons' and describes them as 'particles hitherto unknown to physics' (*Nature*, 1937, **139**, 415). Proceeding with undiminished interest and focus in his famous paper 'On the penetrating component of cosmic radiation' (*Proc. R. Soc.*, 1938, **164**, 257), he estimates the mass of these new particles to be 'as of the order of 100 m'. From a modern point of view this is the first time any particle of the second generation was identified. His contribution in this regard foreshadows that of the Lederman, Steinberger and Schwartz (see Table 1 b).

Box 4

Even a cursory perusal of this paper will show the seminal contributions of several Indians to the field of neutrino physics which will be a central area of study in the coming decades. The remarkable success of the deep underground experiments at Kamiokande have shown the way to go. So it is with a touch of sadness that I remember our wonderful facilities for underground experiments, now closed down at the Kolar Gold Fields, and ask, can we not make a beginning once more?

The result is also of considerable significance for the theory of formation of galaxies and for cosmology. More than a quarter century ago, it was noted^{10,11} that in the early hot and condensed phases of our Universe, the neutrinos even though weakly interacting, would be in thermal equilibrium. As the Universe expands, neutrinos would decouple from radiation and matter and evolve without annihilating each other. By noting that the present-day radiation temperature of the Universe is 2.7 K, it can be shown that the number density of ν and $\bar{\nu}$ of each flavour is $\sim 110 \text{ cm}^{-3}$ when spatially averaged over dimensions of $\sim 10^{27} \text{ cm}$.

Since the density of visible matter in the Universe is very small, $\approx 10^{-8} \text{ H atom cm}^{-3}$ ($\sim 10 \text{ eV cm}^{-3}$), the net density of the invisible low-mass neutrinos (few eV) would considerably exceed the mean density of visible baryonic matter in the galaxies and clusters of galaxies.

Thus, the self-gravity of neutrinos and other such weakly-interacting particles would drive the density fluctuations and be responsible for the formation of galactic systems. It was pointed out¹² that such processes would generically lead to clouds of invisible dark matter surrounding galactic systems and would in turn dominate their internal dynamics, thus explaining the virial discrepancy¹⁵ noted by astronomers in these systems.

It is remarkable that even at the lower limit, $m \geq 0.1$ eV, the mean mass density in neutrinos is ~ 10 eV cm⁻³ which marginally exceeds the mean density of visible matter in the Universe, as estimated from astronomical observations. The density contributed by neutrinos could be much more, constrained^{10,11} only by the so-called Cowsik-McClelland bound of $\Sigma m_\nu < 30$ eV, leading to the critical density of ~ 3 keV/cm⁻³. Thus the Japanese experiments in one stroke have given us a signal of the new physics beyond the Standard Model of particle physics and also confirmed the paradigm proposed more than a quarter of a century ago for the formation of galaxies and for accounting the dark matter in the Universe (Box 4).

In the wake of the remarkable results of the Japanese experiments and the well-appreciated implications to particle physics and cosmology, the study of the neutrino is bound to accelerate and uncover a beautiful landscape in which the microscopic physics of the particles and macroscopic world of astronomy and cosmology seamlessly merge together.

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