Review Article

Mass of the neutrino

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In the standard model (SM) of particle physics, neutrinos are massless and neutral spin ½ particles. But from recent experiments, it is found that neutrinos undergo flavour oscillations, violating lepton flavour conservation which implies that neutrinos have non-zero mass. The absolute scale of neutrino masses is very important for understanding the evolution and the structure formation of the Universe as well as for nuclear and particle physics beyond the present standard model. In this review article, first we have tried to put some logical arguments to support that neutrinos have mass. Then various ways of determining the neutrino masses are briefly discussed and their sensitivities are compared. Neutrino mass is a window for new physics beyond the SM.

Keywords: Neutrino, Special theory of relativity, Neutrinoless double beta decay, Dirac equation

1 Introduction

The existence of the neutrino was postulated by Wolfgang Pauli[1] in 1930, in order to explain the continuous beta spectrum as well as the spin-statistic relation in the beta (β) decay. Neutrinos were introduced as chargeless and massless particles[2-4] to explain something that was missing during beta decay. At first the existence of only one type of neutrino was predicted in β-decay. Pauli's hypothesis was verified around 1953 when the electron-type neutrino (actually the anti-neutrino $\overline{\nu}_e$) produced in a reactor was observed directly by its rescattering by Reines and Cowen[5]. The second neutrino species (flavour), muon-neutrino (ν_μ), associated with μ in its interactions, was detected by its rescattering to produce a muon via $\nu_\mu\, n \to \mu^-\, p (\overline{\nu}_\mu\, p \to \mu^+ n)$ by Danby *et al.*[6] at Brookhaven in 1962. The third neutrino species, tau-neutrino (ν_τ), was observed in 2000 by the DONUT experiment at Fermilab by observing the τ leptons produced via $\nu_\tau\, n \to \tau^-\, p (\overline{\nu}_\tau\, p \to \tau^+ n)$ in a nuclear experiment[7].

According to the Big Bang model, the Universe began 13.7 billion years ago as a tiny region of pure energy that expanded and cooled to create the cosmos we see today. The Big Bang implies: (i) Equal amount of matter and antimatter must have created, and (ii) they should have annihilated with each other. But in our present Universe, we observe more matter than antimatter (*Baryon Asymmetry*). Now, it is believed that the answer to this puzzle could come from the behaviour of the neutrinos. However, these neutrinos themselves are also not free from puzzles. There are three puzzles associated with neutrinos, namely solar neutrino puzzle, atmospheric neutrino puzzle and finally, LSND anomaly. However, these above neutrino puzzles are solved by assuming that "neutrinos have mass" and that neutrino mass eigenstates and weak eigenstates differ, hence, the neutrinos oscillate. The phenomenon of neutrino oscillation was pointed out by Pontecorvo[8]. That is nothing but a quantum mechanical phenomenon in which one type of neutrino flavour can later be measured to have another kind. During 1995, a group of researchers in Los Alamos National Laboratory first found evidence from accelerator collisions that neutrinos can 'oscillate' or transmute from one kind (flavour) to another. But the rationale for why such an oscillation or change implies that neutrinos have mass, has not yet been provided satisfactorily[9-11]. The existence of non-zero neutrino mass was firmly established by the Super-Kamiokande Collaboration[12] in 1998, and intensively studied subsequently. These discoveries represent the first deviations from the SM of particle physics that postulated massless neutrinos and conservation of the individual as well as of the total lepton numbers. Several attempts have been taken to understand the mechanism behind neutrino masses and lepton mixing. Current neutrino experiments measure mass squared differences Δm^2. But the absolute mass of neutrino is not determined so far. In this review article, first we have tried to put

some logical arguments to support that neutrinos have mass. Then various ways of determining the mass of neutrinos are briefly reviewed and their sensitivities are compared.

2 Arguments for the Existence of Neutrino Mass

It is about 11 years since the discovery of the existence of neutrino mass. Here, we have put two different arguments to bring us to this same conclusion i.e. neutrinos must have mass. These are: (i) Relativistic explanation, and (ii) Neutrino's weak interaction.

2.1 Relativistic explanation

Let us consider the relationship between (a) mass and speed and (b) mass and time, as discussed in relativistic mechanics. According to special theory of relativity, only the massless particles can travel with speed 'c', where 'c' is the velocity of light in vacuum. If the particles have some finite mass, they must travel with a speed less than 'c'.

Let us consider a clock is sailing through space at a constant speed v. According to the relativistic equation for time dilation[13]:

$$\Delta t_{\mathrm{m}} = \frac{\Delta t_{\mathrm{s}}}{\sqrt{1 - v^2 / c^2}} = \gamma \Delta t_{\mathrm{s}}, \qquad \dots(1)$$

where $\gamma = \dfrac{1}{\sqrt{1 - v^2 / c^2}}$

Here, Δt_{s} is known as the "proper time" measured by someone who is stationary with respect to the clock. Δt_{m} is the time interval measured by someone with respect to whom the clock is moving with a relative speed v.

From Eq. (1), it is clear that for a massless particle (e.g. photon), any finite interval Δt_{s} will be perceived to be infinite i.e. Δt_{m} = infinite. This means someone at rest on earth watching the photon fly will see its internal clock (clock attach to photon) take infinitely long time between ticks and tocks. He sees (Δt_{m}) the photon's time pass infinitely slow; as if time stops for photon when not interacting with matter, photons are timeless – they can travel for billions of year (Δt_{m} = infinite) without the passage of any corresponding proper time (no change). This would imply that a free photon cannot undergo spontaneous change. Thus, we realise that photons are changeless. We conclude here that photons are changeless as well as timeless.

Now we can put our logical arguments to support neutrinos have mass. If neutrino is massless, it moves at 'c' with $\gamma = \infty$, hence, it must be timeless i.e. $\Delta t_{\mathrm{m}} = \infty$. Consequently, a massless neutrino is changeless. So it cannot spontaneously transform to other form. And it certainly cannot oscillate. But it is observed that neutrinos undergo flavour oscillation; which imply neutrino must have mass. The flavour oscillation does not occur if the neutrinos have zero mass.

2.2 Neutrino's weak interaction

Now we discuss our second type of argument. Neutrinos are chargeless and colourless fermions. Neutrinos do not enjoy the electromagnetic and strong interactions and respond only to weak interactions. According to Dadhich[14], whatever interacts with weak force must be massive and hence neutrino must have non-zero mass, howsoever, small.

3 Mass of the Neutrino

In this section, various ways of determining the mass of neutrinos are briefly discussed and their sensitivities are compared.

3.1 Beta decay

A nucleus with an over abundance of neutrons can transform to a more stable nucleus by emitting an electron and an antineutrino. This kind of process is known as β-decay and the transformation can be denoted by:

$$^{\mathrm{A}}X^{\mathrm{Z}} \rightarrow\ ^{\mathrm{A}}Y^{\mathrm{Z+1}} + e^{-} + \overline{\nu}. \qquad \dots(2)$$

The mass of the neutrino can be determined from the endpoint of the β-spectrum[15]. If $m_{\nu} = 0$, then the endpoint of the spectrum is tangential to the abscissa, whereas if $m_{\nu} \neq 0$, then the endpoint is tangential to the ordinate. Thus, the shape of the β-spectrum near the endpoint can be used to extract the mass of the neutrino. In this case, usually the average electron neutrino mass is determined. In this method, the ultimate sensitivity appears to be $m_{\nu} \sim 0.2$ eV. This mass determination is independent of the Majorana or Dirac nature of neutrinos[16]. The investigation of the endpoint region of a β decay spectrum is still the most sensitive model-independent and direct method to determine the neutrino mass[17].

Recently, the upper limit on the absolute scale of the electron neutrino mass is obtained from the tritium beta decay[18] as $m(\nu_{\mathrm{e}}) < 2$ eV.

3.2 Neutrinoless double beta decay

Double beta decay (ββ)is a nuclear transition (Z, A) → (Z+2, A) in which two neutrons bound in a nucleus are simultaneously transformed into two protons plus two electrons (there may be some light particles also). Analogous transition of two protons into two neutrons is also occurred in several nuclei.

There are three main modes of ββ decay[19]: (i) In the two-neutrino decay mode (2v ββ), there are $2\overline{v}_e$ emitted together with $2e^-$. The lepton number is conserved for this mode and this mode of decay is allowed in the standard model of electroweak interaction. (ii) In the neutrinoless double beta decay mode (0v ββ), only the $2e^-$ are emitted and nothing else. This neutrinoless double beta decay occurs when the two antineutrinos, instead of manifesting themselves as real states, "annihilate". This can only occur if neutrinos are their own antiparticles[20,21]. This mode violates the law of lepton number conservation and is forbidden in the standard model. Hence, its observation may lead to a signal of new physics. The lepton number violation can generate a lepton asymmetry in the early Universe, which will be able to explain the present baryon asymmetry of the Universe. (iii) (0$v\chi^0$ββ) decay mode requires the existence of a Majoron. It is a massless Goldstone boson that arises due to breakdown of (B-L) symmetry, where B and L are the baryon number and the lepton number, respectively. If the Majoron exists, it could play a significant role in the history of the early Universe and in the evolution of stars. The two-neutrino double beta decay is already experimentally observed. But neutrinoless double beta decay has not yet been observed. The possible exception is the result with ^{76}Ge. The existence of 0v ββ decay is closely related to some fundamental aspects of particle physics like lepton number non-conservation, the existence of massive neutrino[22] and its origin, the existence of right-handed currents in electroweak interactions, the structure of the Higgs sector, supersymmetry, the existence of lepto-quarks, the existence of a heavy sterile neutrino and the existence of a composite neutrino. All of these phenomena are beyond the standard model of elementary particle physics. Therefore, the detection of 0v ββ decay would be a signal for the discovery of new physics.

Neutrinoless double beta decay corresponds to an atomic nucleus changing two of its neutrons into protons, while emitting two electrons. At the quark level, the 0v ββ process corresponds to the simultaneous transition of two down quarks (in different neutrons) into two up-quarks and two electrons, but no neutrinos ($dd{\rightarrow}uu+e^-e^-$). If 0v ββ decay is discovered, it would imply that neutrinos are Majarana particles[23]. Current neutrino experiments measure mass squared differences Δm^2, but do not measure the absolute neutrino masses. Previously, it was believed that the 0v ββ decay can probe absolute neutrino mass scale, but now after the discovery of large neutrino mixing it is clear that apart from few particular cases the 0v ββ decay probes some combination of masses and mixing. The 0v ββ decay does not allow a very precise neutrino mass determination due to the unknown Majorana phases and the uncertainties of the nuclear matrix elements.

Assuming Majorana nature of neutrino, a strong limit on the mass eigenstate of v_e is obtained as $m_{v1}{\leq}$0.4-0.5 eV from neutrinoless double beta decay experiments with Germanium[24,25] and Tellurium[26,27]. Furthermore, the search for the 0v ββ decay is the only way to probe the Majorana nature of neutrinos (i.e. the neutrino and antineutrino are identical) and one of the most promising ways to search for lepton number violation.

3.3 Neutrino oscillations

In this method, neutrino mass squared differences $\Delta m_{ij}^2 = m_i^2 - m_j^2$ are determined. The two different Δm^2 values are $\left| \Delta m_{atm}^2 \right| = \left(1.9 - 3.0 \right) \times 10^{-3}$ eV^2 and $\Delta m_{sol}^2 = 8.0_{-0.3}^{+0.4} \times 10^{-5}$ eV^2. This range and indicated error bars show the present sensitivity. This mass determination is independent of the charge conjugation properties of neutrinos.

3.4 Cosmological observations

From cosmic microwave background and large scale structure data, the size of fluctuations is observed at different scales. Since the light neutrinos would have smeared out fluctuations at small scales, the power spectrum at small scales is sensitive to the neutrino mass. Although the absolute mass of the neutrinos has not yet been determined, there is an upper bound on the sum over all neutrino masses from cosmological observations[28]:

$$\sum_{i=e,\mu,\tau} m_{v_i} \leq 0.61 \text{ eV},$$

which are to some extent model and analysis dependent[29]. This mass determination is independent of the Majorana or Dirac nature of neutrinos.

3.5 Theoretical studies

Numerous theoretical models are proposed to determine the absolute mass of neutrinos but none evoke the clear ring of truth till today. A few of them are discussed briefly:

(a) In the theory of Dirac equation and in the standard model, the neutrino is massless and chargeless particle. Recently, Sidharth[30] has studied the Dirac equation in quantized space-time[31], where the space-time is discrete and coordinates do not commute. In discrete space-time structure, the energy momentum relation is modified as[32,33]:

$$E^2 = m^2 + p^2 + \alpha\eta^2 p^4, \qquad \dots (3)$$

where α is positive and η is the minimum fundamental length, the Planck length or the Compton length. Eq. (3) represents Snyder-Sidharth Hamiltonian.

Let us now consider the Dirac equation:

$$\left(\gamma^\mu p_\mu - m\right)\psi \equiv \left(\gamma^0 p^0 + \Gamma\right)\psi = 0 \qquad \dots(4)$$

Under the influence of Eq. (3), we can write:

$$\left(\gamma^0 p^0 + \Gamma + \beta\eta\, p^2\right)\psi = 0, \qquad \dots(5)$$

where β is a matrix, which satisfy

$$\Gamma\beta + \beta\Gamma = 0, \quad \beta^2 = 1 \quad \text{and } \beta = \gamma^5 \qquad \dots(6)$$

Now, using Eq. (6) in (5), the modified Dirac equation becomes:

$$\left(\gamma^0 p^0 + \Gamma + i\,\alpha\,\gamma^5\,\eta\, p^2\right)\psi = 0 \qquad \dots(7)$$

This is known as Dirac-Sidharth equation[30]. This equation can be written as:

$$\left(D + i\,\alpha\,\gamma^5\,\eta\, p^2\right)\psi = 0, \qquad \dots(8)$$

where D represents the usual Dirac operator. The extra term in Eq. (8) represents a mass term. Eq. (8) is valid both for a massive and a massless Dirac particle. Let us consider the case of a massless Dirac particle for example neutrino. Now, Eq. (8) represents the neutrino with a mass. Thus, a massless particle, satisfying the Dirac equation in the usual theory acquires a mass due to the Snyder-Sidharth

Hamiltonian. This theoretical method is independent of the Majorana or Dirac nature of neutrinos.

(b) Krolikowski has proposed a neutrino mass formula in Ref. (34). This formula predicts all three neutrino masses as $m_1 \approx 2.5\times10^{-3}$ eV, $m_2 \approx 9.3\times10^{-3}$ eV and $m_3 \approx 5.0\times10^{-2}$ eV, when two experimental estimates $\Delta m^2_{21} \approx 8.0\times10^{-5}$ eV^2 and $\Delta m^2_{32} \approx 2.4\times10^{-3}$ eV^2 are used as an input. This mass determination is independent of the Majorana or Dirac nature of neutrinos. These values show the present sensitivity.

(c) Seesaw mechanism The most popular mechanism of the generation of small neutrino masses is the seesaw mechanism[35,36]. In Type-I seesaw mechanism[37-42], right-handed neutrinos with very large Majorana masses are added to the SM. These right-handed neutrinos induce a very small mass for the left-handed neutrinos (which is proportional to the inverse of heavy mass) through the Type-I seesaw formula i.e. the mass matrix of light neutrinos is given by $M_\nu = M_D M_R^{-1} M^T_D$, where M_D is the Dirac mass matrix linking left-handed light neutrinos to right-handed heavy neutrinos and M_R is mass matrix of heavy Majorana neutrinos. Actually, there are three tree-level seesaw scenarios (Type-I, Type-II (Refs 43-46) and Type-III (Ref. 47) seesaw mechanisms) and one loop-level seesaw scenario (Ma[48] model). In the seesaw mechanism, the mass of heavy seesaw particle is too heavy, close to the GUT scale $\sim 10^{14}$–10^{16} GeV, which is completely unrelated to the mass scale of the SM. Thus, the heavy right-handed neutrinos gives the signature of new physics beyond the SM. If we lower the seesaw scale down to the TeV Scale[36] then it is possible to detect at the Large Hadron Collider. The smallness of the neutrino mass is associated with the heaviness of the right-handed neutrino mass[49,50]. If we take $M_D = M_W = 80$ GeV and $M_R = M_{GUT} = 10^{16}$ GeV then we find $M_\nu \sim 10^{-3}$ eV which looks good for solar neutrinos. Atmospheric neutrino masses would require a right-handed neutrino with a mass below the GUT scale. But the seesaw mechanism is very difficult to test. If the seesaw mechanism in its simplest form is correct, then it could explain the matter-antimatter asymmetry in the Universe through a mechanism known as leptogenesis. However, this would require both Majorana masses and CP violation, neither of which have been experimentally established.

It is expected that our discussion will stimulate to both experimenters and model builders. We hope the combination of all the above methods will provide the absolute scale of neutrino masses.

4 Conclusions

Hence, it is clear that neutrinos must have non-zero mass,howsoever, small (< 0.50 eV). Then question arises: What happens if neutrinos do possess some mass? Astronomers and cosmologists, after several decades of observations, find that the bulk of the mass in the Universe is unseen and this has been given the name – dark matter[28,51-54]. Neutrinos with mass may be one of the candidates for the dark matter. Small neutrino masses are sensitive to new physics at scales ranging from a TeV up to grand unification and superstring scales. The very smallness of neutrino mass leads many theorists to believe that they provide a window on physics at much higher energies than our accelerator can reach. Neutrinos are important for the study of the sun, stars, core-collapse supernovae, the origins of the cosmic rays, the large-scale structure of the Universe, big bang nucleosynthesis, and possibly baryogenesis. These tiny neutrino masses are of great interest because they might arise from some fundamentally different mechanism to the way the masses of other particles are generated i.e. the Higgs mechanism. Although the SM is very successful to explain many low as well as high energy phenomena in particle physics but within the framework of this model, it is not possible to realize the massive neutrinos. The existence of neutrino mass is one of the signatures of new physics beyond the SM[55-57].

Finally,we must mention that even the fundamental nature of the neutrino is still not known, namely whether neutrino is its own antiparticle or not (Majorana or Dirac particle). This question can be answered by the "neutrinoless double beta decay". Neutrinoless double beta decay is the only experiment that can probe the Majorana nature of the neutrino[58]. So far, such experiments have not yielded definite results and hence, more experiments are being planned. There are several new neutrino experiments under construction and some of them are ready to take data. The aim of these experiments would be to study the neutrino oscillations, search for neutrinoless double beta decay, measurement of absolute neutrino mass and the nature of neutrinos. The study of neutrino physics and the implications of the results connect many disciplines together, from particle physics to nuclear physics to astrophysics to cosmology. Thus, neutrino physics continues to be a very exciting field and may also bring us new surprises in this 21st century.

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