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Neutrinos –Past, Present and Future

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ABSTRACT

Neutrinos are well known elementary particle like an electron. The discovery of neutrino oscillation has provided us with the first (and so far only) conclusive experimental evidence of physics beyond the Standard Model. Therefore, it is very important to explore the experimental signatures of neutrino mass models, which might lead to some crucial insights into the underlying new physics. The story of its discovery is discussed, in detail. The current status and the future prospects of neutrino mass generation, in particular, the ongoing searches through neutrino oscillation experiments are summarized.

Keywords : Neutrinos, Standard Model, Mixing angles, Oscillation experiments, Neutrinoless double beta decay

I INTRODUCTION

Neutrinos are well known elementary fermion particle like an electron but are neutral. They are spin half particles. Their rest mass is so small that they were regarded as massless particles. They are produced in large numbers through various processes and move almost with the speed of light. In every second more than 10^{12} neutrinos hit our body, without affecting us. We require huge detectors and sophisticated instruments to study neutrinos that pass through all the matter.

Standard Model (SM) was developed in the late 20th century to unify the three basic forces electromagnetic, weak and strong. It is a complete theory but the major drawback is to place these right handed neutrinos. Neutrinos are massless in SM but the experimental signs related to neutrino oscillation verified that the neutrinos have mass which is a clear signal to go beyond the SM. Therefore, it is very important to explore the experimental signatures of neutrino mass models, which might lead to some crucial insights into the underlying new physics. Thus, to understand its significance, it is essential to look past, present and future of neutrinos.

II PAST STATUS

The story of neutrino started back from the time of 19th century when Becquerel discovered radioactivity. Neutrino, a neutral particle with spin half were discovered, to ensure the conservation of energy in β-decay by Pauli[1]. Fermi[2] wrote famous four Fermi Hamiltonian using neutrino, electron, neutron and proton. The theory formulated by Pauli and Fermi was not accepted by Reins and Cowan and concluded that it is only acceptable if the existence of neutrinos were experimentally proved. Afterwards, emission of antineutrinos from the nuclear detector was experimentally proved by Reins and Cowan[3] in 1954 and Reins received the Nobel Prize for this in 1955 but at that time Cowan passed away.

The theory was further generalized by Marshak and Sudarshan[4] and then by Feynman and Gell-Mann[5], referred as V-A theory of weak interactions. Further, the theory had been extended to unify electro-weak forces carried out by Glashow, Weinsberg and Salam[6] and furthermore extended to include strong forces resulting in unified Standard model.

Pontecarvo[7] considered the transition of antineutrino to neutrino. In 1962, second flavor neutrino was discovered by Danby *et al*.[8]. The third flavor ν_τ was expected to exist after the discovery of charged lepton τ in 1975 and was observed in 2000 by DONUT Collaboration Perl *et al.*[9] in Fermi Lab. The late discovery of lepton indicates the flavor puzzle existence, not only for quarks but for leptons as well.

III NEUTRINO OSCILLATIONS

The major milestones in high energy physics is the discovery of the Higgs boson at the Large Hadron Collider at CERN[10]. The discovery completes the picture of Standard Model (SM) but the theory cannot explain massive neutrinos i.e. position of right handed neutrinos in SM. The absence of right handed neutrinos is motivated by the observation of parity violation in weak interactions by Lee and Yang[11] and further verified by Wu ^{60}Co experiment[12]. Neutrino physics has been full of excitement and rich in its implications for New Physics beyond Standard Model (BSM).

The quantum mechanical treatment is applied to neutrinos and treated them as waves. For the neutrino wave, we have the three flavors of neutrino (ν_1, ν_2, ν_3) and the mass eigenstates (ν_e, ν_μ, ν_τ). As an example, the e^- type neutrinos are produced in the core of the sun, propagates as a superposition of three mass eigenstates. As they travel further, they pick up different phases which are recombined to form a flavor state at the point of detector. Now, the wave will have μ and τ component both along with the initial e component. This is what we called as neutrino oscillations. Since the neutrino oscillation is an oscillatory phenomenon, the probability of flavor conversion is represented by the oscillatory functions of the distance travelled by the neutrino wave, the characteristics length proportional to average energy of neutrinos and inversely proportional to difference of the square of the masses. The overall probability is controlled by mixing coefficients and that occur in the superposition of mass eigenstates to flavor states and this mixing coefficients form mixing matrix

Neutrinos originate from different sources having energy ranging from few eV to TeV. Most of the solar neutrinos are generated from the p-p fusion inside the sun whereas reactor and geo-neutrinos originate from the β- decay process in the MeV energy range. The neutrinos coming from the supernova explosions are generated through the electron capture of nuclei and free protons as well as through pair production are also in MeV range. The interactions of the cosmic rays with the atmospheric nuclei produce neutrinos in the GeV range and the neutrinos coming from the extragalactic sources fall in the energy range of TeV. The neutrinos produced in the man-made accelerators can have energy in MeV or GeV. The highest energy neutrinos are produced due to interaction of the ultrahigh energy cosmic rays with cosmological photon backgrounds. They could also be produced in the interactions of accelerated protons with surrounding medium.

Among these different sources, the experimental evidences come from a series of experiments performed during the decades of research with very different beams and detection techniques. These include the solar neutrino experiments[13-16], e.g., Homestake, Kamiokande, SAGE, GALLEX-GNO, Super-Kamiokande (SK) and the Sudbery Neutrino Observatory (SNO); the atmospheric neutrino experiments,i.e., Super-Kamiokande, MACRO and Soudan-2; the Long Baseline reactor neutrino experiment KamLAND and the Long Baseline accelerator neutrino experiment KEK-to-Kamioka (K2K).

IV PRESENT STATUS

The phenomena of neutrino oscillation and flavor mixing can be described by Pontecorvo-Maki-Nakagawa-Sakata[7] (PMNS) mixing matrix V_{PMNS}, expresses the relationship between the neutrino mass eigenstates and the flavor eigenstates, e.g.,

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} V_{e1} & V_{e2} & V_{e3} \\ V_{\mu 1} & V_{\mu 2} & V_{\mu 3} \\ V_{\tau 1} & V_{\tau 2} & V_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix};$$

where ν_e, $\nu_{\mu,}$,ν_τ are the flavor eigenstates and ν_1, $\nu_{2,}$,ν_3 are the mass eigenstates and the 3×3 mixing matrix is leptonic mixing matrix. It is usually parameterized by three mixing angles (θ_{12}, θ_{13}, θ_{23}) and 1 CP violating phase (δ). If neutrinos are Majorana particles, there results in additional two phases (ρ, σ) related to two relative phases of three neutrino mass eigenstates. The current status of neutrino oscillation experiments[17] can be summarized in terms of 3σ global fit values of neutrino parameters.

$$\Delta m^2_{12}\,\mathbf{(10^{-5}eV^2)} = 7.50^{+0.19}_{-0.17} \qquad \Delta m^2_{31}\,\mathbf{(10^{-5}eV^2)} = 2.457 \pm 0.047$$

$$\mathbf{\sin^2\theta_{12}} = 0.304^{+0.013}_{-0.012} \qquad \mathbf{\sin^2\theta_{23}} = 0.452^{+0.052}_{-0.028} \qquad \mathbf{\sin^2\theta}_{13} = 0.0218 \pm 0.0010$$

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where $\theta_{12,}$ $\theta_{13,}$ and θ_{23} are mixing angle and Δm^2_{12} and Δm^2_{31} are the mass square differences.

Neutrinoless double β decays provide us with useful information regarding the nature of neutrinos and CP violation. The tritium beta decays in Mainz and Troisk experiments[18] observed the experimental value of effective neutrino mass $m_\beta < 2.2$ eV at 95% C.L. But, there is no clear signal regarding the $0\nu 2\beta$decay uptil now. The most stringent bound on half life of ^{136}Xe by KAMLAND-Zen Collaboration[19] on Majorana neutrino mass $\langle m_{ee} \rangle <$ (0.061 -0.165) eV. The latest searches have been performed by CMS and ATLAS[20] for the seesaw, too high as 10^{14}GeV as compared to 10^2GeV neutrino mass. Finally, the observation of cosmic microwave background would constrain the sum of three neutrino masses $\Sigma = m_1+m_2 +m_3$ and latest observation by Planck Collaboration[21] gives $\Sigma < 0.23$eV at 95% C.L.

V FUTURE PROSPECTS

At present the current experimental scenario lag behind to explain (i) the sign of θ_{13} or the neutrino mass hierarchy, (ii) the octant of θ_{23} (i.e., whether $\theta_{23} < 45^\circ$ or $> 45^\circ$) and (iii) CP violation in leptonic sector and the precision of δ_{CP}. Apart from these, the following unresolved issues are also of interest: (i) the absolute mass of the neutrinos, (ii) the exact nature of the neutrinos i.e., Dirac or Majorana, (iii) the mechanism of generation of neutrino masses and explanation of their smallness, (iv) non standard interaction of the neutrinos, (v) non-unitary neutrino mixing and (vi) CPT violation in neutrino oscillation etc.

There are many ongoing/ future experiments are in pipeline for determining the unknown parameters precisely, the neutrino mass ordering and CP violation. In the near future, KATRIN experiment[22] would pin down the value of effective neutrino mass< 0.2 eV. If the neutrinos are considered to Majorana neutrinos, the neutrinoless double beta decay ($0\nu2\beta$) could take place for some even even nuclei such as ^{76}Ge and ^{136}Xe. The long baseline neutrino experiments such as NovA, DUNE, T2K[23] aim is to measure the leptonic phase δ_{CP}. The longer baseline and higher statistics experiments LBNE and LBNO[24] can measure all the three above mentioned unknowns with significant confidence level. The DAEδLUS[25] experiment proposes to replace the antineutrinos of the superbeam experiments by the low energy antineutrinos from muon decay at rest and using Gd-doped water Cerenkov detector. The superbeam[26] experiment at the ESS facility namely MOMENT, ESSνSB reach the competitive sensitivity for establishing the CP violation.

The future reactor neutrino experiments[27] such as RENO, JUNO are used to determine the mass hierarchy using liquid scintillator detector. These experiments require the precise measurement of the oscillation spectrum with an excellent energy resolution. The future huge atmospheric neutrino experiments[28] such as PINGU, ORCA, ICAL@INO, hyper Kamiokande are sensitive to sign of mass square differences, results in explaining the mass ordering of neutrinos. Also, these experiments are sensitive to leptonic CP violation. The main aim of the $0\nu2\beta$ and ultra high energy neutrino detector IceCube[29] at South Pole is to understand the origins and acceleration mechanisms of high-energy cosmic rays. This somewhat completes the story of neutrinos.

VI SUMMARY

Neutrino Oscillations have provided us with the first signal to search for the New Physics beyond standard Model. We have done the review of past, current and future prospects of neutrinos. The future experiments would definitely provide us the precise values of the mixing angles, ordering, nature of neutrinos and CP violation. Thus, the direct searches at these huge colliders give us clear picture of the story of neutrinos.

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