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Neutrino Physics: Status and Open questions

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Abstract

Overview of the status of the present knowledge of neutrino physics, including measurements of $\nu_\mu \rightarrow \nu_e$ oscillation and θ_{13}, an initial test of CP violation, the neutrino-less double beta decay, high energy astrophysical neutrinos, and sterile neutrinos, is given.

Keywords: neutrino oscillations, CP violation, neutrino mass, sterile neutrinos, astrophysical neutrinos

1. Introduction

Why is the study of neutrinos important? Some simple answers are they have small but non-zero masses, they mix and individual lepton numbers are not conserved. This is in conflict with the postulates of the Standard Model (SM) which assumes that there are three types (flavors) of massless active neutrinos which cannot change their flavor during their propagation in space as they travel at the speed of light, *i.e.* cannot mix with each other. Presently the study of neutrinos is our only known window into physics beyond the SM.

Neutrino oscillations, predicted by B. Pontecorvo [1], are naturally described by a simple and widely accepted extension to the SM in which three flavor eigenstates ν_e, ν_μ, and ν_τ are connected to the neutrino mass eigenstates ν_1, ν_2, and ν_3, respectively, by a 3×3 unitary matrix, known as the PMNS matrix U [2] which can be parametrized in terms of three mixing angles θ_{12}, θ_{23}, θ_{13}, and a CP violating phase δ_{CP}. The neutrino mixing angles and the mass splittings have been measured by atmospheric, solar, reactor and accelerator experiments with a precision of several percent. Despite the exciting results obtained in neutrino physics in the last few decades we still have a number of fundamental questions to be answered. What is the neutrino mass hierarchy: normal ($m_3 \gg m_2 > m_1$) or inverted ($m_2 > m_1 \gg m_3$)? What is the absolute neutrino mass scale? Is the CP symmetry violated in the lepton sector? What is the nature of neutrinos: Dirac or Majorana particles? What is the mechanism of the origin of the neutrino mass and mixing? Do sterile neutrinos exist? Our present understanding of the answers to these questions are briefly described below.

2. $\nu_\mu \rightarrow \nu_e$ and θ_{13}

During the last three years, exciting results were obtained by both accelerator and reactor oscillation experiments. For the first time neutrino oscillations were measured in the "appearance" mode: the long baseline experiment T2K [3] has made the first direct observation of electron neutrino appearance in a muon neutrino beam. A total of 28 electron neutrino events were detected in an almost pure muon neutrino beam [4]. The expected background in the absence of $\nu_\mu \rightarrow \nu_e$ oscillation ($\theta_{13} = 0$) is estimated to be 4.92 ± 0.55 events. The energy distribution of the 28 events is shown in

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Fig. 1. The significance of a nonzero θ_{13} is calculated to be 7.3σ. Precise measurements of this angle were provided by reactor experiments Daya Bay [5], RENO [6], and Double Chooz [7] which observed $\bar{\nu}_e \rightarrow \bar{\nu}_e$ disappearance and obtained a combined value of $\theta_{13} = 9 \pm 0.5$ degrees. We now know that all the three mixing angles θ_{12}, θ_{23}, and θ_{13} of the PNMS matrix have nonzero values and a large mixing between different neutrino flavors exists.

3. CP Violation in Neutrino Oscillations

Large mixing and especially a large value of θ_{13} gives us an opportunity to search for CP violation in neutrino oscillations *i.e.* CP violation in the lepton sector. The Jarlskog parameter J_{CP} which characterizes the strength of CP violation has the following form for neutrinos

$$J_{\rm CP}^{PMNS} = \cos\theta_{12}\sin\theta_{12}\cos^2\theta_{13}\sin\theta_{13} \times \cos\theta_{23}\sin\theta_{23}\sin\delta_{CP}. \quad (1)$$

This parameter has a non-zero value if $\sin\delta_{CP} \neq 0$. In the quark sector, $J_{CP}^{CKM} \sim 3 \times 10^{-5}$, while for the lepton sector $J_{CP}^{PMNS} \sim 0.035\sin\delta_{CP}$. The Baryon Asymmetry of the Universe (BAU) cannot be explained by CP violation in the quark sector due to the smallness of J_{CP}^{CKM}. Considering the large mixing angles, CP violation in the lepton sector can in principle be very significant. The discovery of CP violation in neutrino oscillations together with non-conservation of lepton number may provide important clues that will favor the explanation of the BAU through the leptogenesis mechanism. How can CP violation be observed and δ_{CP} measured in neutrino oscillations? The T2K discovery of the $\nu_\mu \rightarrow \nu_e$ transition may help us answer these questions. The CP asymmetry

$$A_{CP} = \frac{P(\nu_\mu \rightarrow \nu_e) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)}{P(\nu_\mu \rightarrow \nu_e) + P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)} \simeq \simeq \frac{\Delta m_{23}^2 L}{4E} \cdot \frac{\sin 2\theta_{12}}{\sin\theta_{13}} \sin\delta_{CP} \quad (2)$$

can be measured with an off-axis narrow band beam of muon neutrinos and anti-neutrinos at the neutrino energy E and baseline L tuned to the oscillation maximum for $\Delta m_{23}^2 \simeq 2.4 \times 10^{-3}$ eV^2. Another approach is to measure the oscillation with a wideband neutrino and anti-neutrino beam using the first and second oscillation maxima. The shape of the energy spectra of oscillated electron neutrinos and anti-neutrinos (intensities and energies corresponding to the 1st and 2nd oscillation maxima) depend on δ_{CP}. If mass hierarchy is known, such a method allows one to measure δ_{CP} using only a neutrino beam. It should be noted that the presence of matter creates a "false" CP-odd effect, which needs to be separated from the "true" CP violation.

An initial search for CP violation can be done using θ_{13} measurements in long baseline accelerator experiments and reactor experiments. The combination of the T2K result with the value of θ_{13} measured in the reactor experiments [8], as shown in Fig. 2, allowed one to obtain the first experimental bounds on the CP-odd phase. This combination prefers $\delta_{CP} = -\pi/2$ for both mass hierarchies and excludes most of the CP phase region between 0 and π. It should be noted that after analysis of their neutrino and anti-neutrino data, the MINOS experiment obtained a best fit value for δ_{CP} around $\pi/2$ [10]. The search for CP violation in neutrino oscillations has just started and we can expect new results from running experiments T2K and NOνA in the near future.

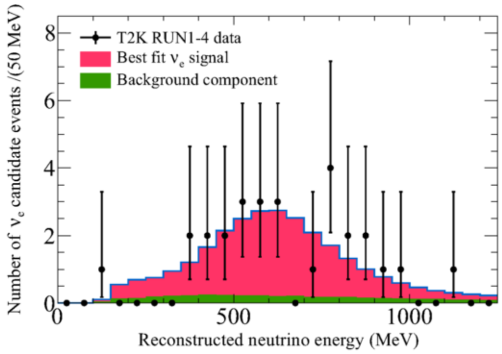

Figure 1: Energy distribution of the T2K ν_e events. The fit shown assumes normal mass hierarchy (light-red) and the background is in dark (green).

4. Direct Neutrino Mass Measurements

The absolute scale of neutrino masses cannot be determined in oscillation experiments since they are sensitive only to Δm^2. A small but direct and model independent effect of the neutrino mass can be potentially measured in the low energy nuclear beta decay $H^3 \rightarrow He^3 + e^- + \bar{\nu}_e$. The active $\bar{\nu}_e$ is a mixture of three (if no sterile neutrinos exist) mass eigenstates ν_1, ν_2, and ν_3 with an effective mass of $m_{\bar{\nu}_e}^2 = \sum_i |U_{ei}|^2 m_i^2$. Two past tritium experiments obtained the following upper limits on the neutrino mass: Troitsk nu-mass: $m(\bar{\nu}_e) < 2.05$ eV at 95%CL [11] and Mainz experiment: $m(\bar{\nu}_e) < 2.3$ eV at 95% confidence level [12]. The next generation tritium experiment KATRIN is expected to start data taking in 2016. This experiment can achieve a sensitivity of

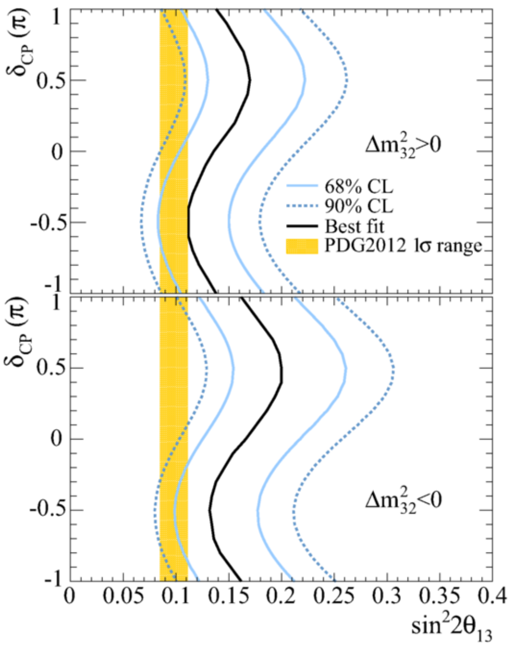

Figure 2: The 68% and 90% CL allowed regions for $\sin^2 2\theta_{13}$, as a function of δ_{CP} assuming normal hierarchy (top) and inverted hierarchy (bottom). The solid line represents the best fit $\sin^2 2\theta_{13}$ value for given δ_{CP} values. The values of $\sin^2\theta_{23}$ and Δm^2_{32} are varied in the fit with the constraint from the T2K disappearance result [9]. The shaded region shows the average θ_{13} value from the reactor experiments [8].

approximately 0.2 eV (90% CL) for the neutrino mass with a discovery potential (3σ level) of ~0.3 eV.

5. Neutrino-less 2β Decay

Several extensions of the SM predict the existence of neutrino-less double beta decay ($0\nu\beta\beta$). This implies that the reaction $(A, Z) \to (A, Z + 2) + 2e^-$ should be observed experimentally. It's discovery would imply that total lepton number is violated, neutrinos are Majorana particles, and the absolute neutrino mass scale can be probed with high sensitivity. Knowing if the neutrino is a Majorana or Dirac particle is very important for understanding of the origin of small neutrino masses. The $0\nu\beta\beta$ decay rate is proportional to the square of the so-called effective Majorana mass $|m_{\beta\beta}|$ which is defined through the mass eigenstates and elements of the PMNS matrix as follows: $|m_{\beta\beta}| = |\sum_i U^2_{ei} m_i|$. Fig. 3 shows the effective neutrino mass $|m_{\beta\beta}|$ as a function of the lightest neutrino mass. Current $0\nu\beta\beta$ experiments probe the effective Majorana masses in the degenerate hierarchy region. For the inverted hierarchy scenario the range of effective Majorana masses is 10–50 meV. Running and future accelerator, reactor and atmospheric oscillation experiments have a potential to determine the mass hierarchy in the next 10-20 years. Searches for $0\nu\beta\beta$-decay in future projects (MAJORANA, EXO, KamLAND-Zen, SNO$^+$) with a sensitivity of 20-50 meV will be able to initially test the Majorana nature of neutrinos in the region of the inverted mass hierarchy [14]. If a limit on the effective mass will be below the range of $|m_{\beta\beta}|$ values for the inverted hierarchy, this order is ruled out if neutrinos are Majorana particles. In case the mass hierarchy is known to be inverted, from oscillation experiments, then the Majorana nature of neutrinos would be ruled out.

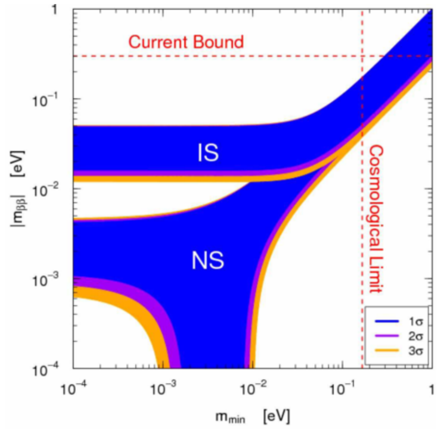

Figure 3: Effective neutrino mass $|m_{\beta\beta}|$ as a function of the lightest neutrino mass in case of inverted (IS) and normal (NS) hierarchy. Current bounds show the upper limit on $|m_{\beta\beta}|$ from $0\nu\beta\beta$ experiments. The shaded areas correspond to $1\sigma, 2\sigma, 3\sigma$ uncertainties [13].

6. High Energy Astrophysical Neutrinos

The IceCube detector provided the first observation of high energy astrophysical neutrinos and has opened a new era of high energy neutrino astrophysics [15]. Fig. 4 shows the energy distribution of 37 high energy neutrino events. A purely atmospheric explanation for these events is rejected at the 5.7σ level. No significant spatial clustering was observed and the origin of these events is unknown.

7. Sterile Neutrinos

The completeness of the three-neutrino mixing scheme parametrized by the PMNS matrix is challenged by indications on the existence of intriguing anomalies obtained in several short baseline experiments that cannot be accommodated within this paradigm. The LSND experiment [16] observed a 3.8σ excess of $\bar{\nu}_e$

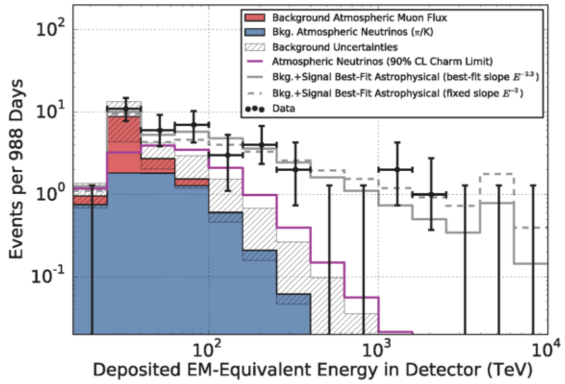

Figure 4: The distribution of observed deposited energy in IceCube.

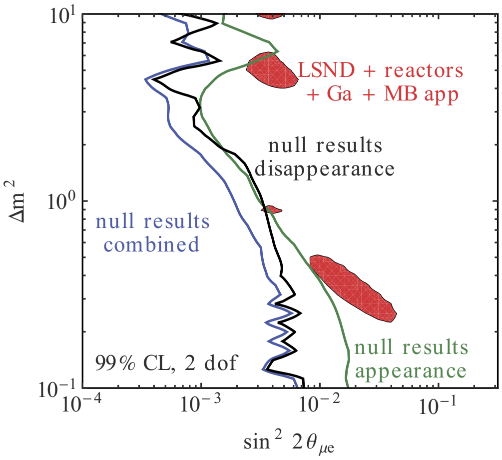

Figure 5: Allowed regions for the effective mixing angle $\sin^2 2\theta_{\mu e} = 4|U_{e4}|^2|U_{\mu 4}|^2$ and Δm^2_{41} in the 3 + 1 scenario [21]. Shaded (red) areas show regions preferred by experiments reported positive signals on sterile neutrinos (LSND and MiniBooNE appearance, reactor and Ga deficit). Right (green) and middle (black) lines show constraints from appearance and disappearance experiments, respectively. The left (blue) line shows the combined exclusion limit.

events, a ν_e 3.4σ and 2.8σ $\bar{\nu}_e$ excesses were observed by MiniBooNE [17] in short baseline experiments using muon neutrinos and anti-neutrinos. The deficit of $\bar{\nu}_e$ events (0.937 ± 0.027) was observed by reactor neutrino experiments [18] and the disappearance of ν_e events (0.86 ± 0.05) was observed in the SAGE [19] and GALLEX [20] experiments using radioactive sources. These anomalies, if correct, hint at the existence of at least one additional neutrino with a mass of ≥ 1 eV. From the LEP measurements of the invisible width of the Z boson we know that there are only three active neutrinos and therefore the additional massive neutrinos, if they do exist, correspond to sterile neutrinos, which do not participate in weak interactions. The aforementioned results are contrasted with a number of results which clearly disfavor this interpretation. The strongest constraints are derived from the non-observation of muon neutrino disappearance by accelerator experiments KARMEN, CDHS, NOMAD, MINOS, ICARUS and others. Results of the global fit in the 3 + 1 scenario [21], including positive signals and constraints from appearance and disappearance experiments, are shown in Fig. 5. There is a strong tension between signals preferring oscillations with $\Delta m^2 \geq 1$ eV^2 and null-result data. From these data we see an incomplete and contradictory picture and therefore more conclusive tests to confirm or refute the sterile neutrino hypothesis are needed and a large number of new experiments [22] are proposed to test the LSND, reactor and Ga anomalies.

From a theoretical standpoint the existence of sterile neutrinos is a rather natural consequence of neutrinos having a non-zero mass. Once neutrino mass generation via the see-saw mechanism is put into the wider context of grand unification and leptogenesis, light sterile neutrinos (~ 1 eV) are slightly less natural. An extension of the SM by three singlet fermions (heavy sterile neutrinos) with masses smaller than the electroweak scale without adding any new physical principles allows one to explain simultaneously the phenomena that cannot be fit to the SM such as the neutrino mass, dark matter, and BAU. An example of such a theory is the νMSM (neutrino Minimal Standard Model) [23]. In this model, the lightest sterile neutrino $(\nu_H)_1$ with a mass of $O(10)$ keV has a very weak mixing with the other leptons, playing no role in active-neutrino mass generation, and sufficiently stable to be a viable dark matter candidate. Direct constraints on parameters of $(\nu_H)_1$ are obtained from $0\nu\beta\beta$ experiments. The heavy neutrinos $(\nu_H)_2$ and $(\nu_H)_3$ should be nearly degenerate in the mass range from ~ 150 MeV to 100 GeV ($\Delta M_{2,3} \ll M_{2,3}$) to generate the BAU. Due to the mixing with active light neutrinos heavy neutrinos can be produced in weak decays of heavy mesons and can also decay into SM particles. The constraints on the mixing parameter between active and heavy neutrinos $|U_{\mu H}|^2$ in the mass region 0.1 – 100 GeV are shown in Fig. 6. One can expect that the fixed target experiment SHIP proposed at CERN will cover a major fraction of the unexplored mixing parameter space for masses between 0.5 – 2.0 GeV.

8. Conclusions and Prospects

Neutrinos have become an important laboratory to study physics beyond the SM. The recently measured

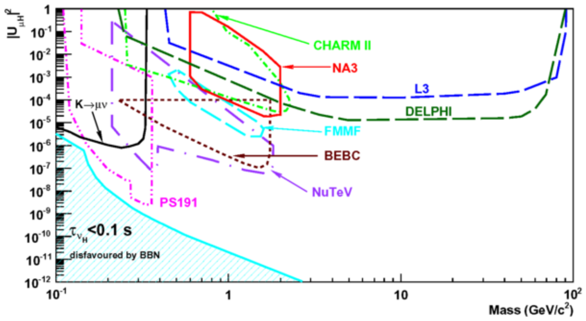

Figure 6: Bounds from various experiments on $|U_{\mu H}|^2$ in the mass region 0.1 – 100 GeV [24].

large value for θ_{13} opens a door to mass hierarchy and δ_{CP} determination in neutrino oscillations. A continuing theoretical question is $\delta_{CP} \neq 0$ an indication of leptogenesis and the origin of the BAU. Neutrinoless 2β decay can be detected in case of inverted mass hierarchy in the near future and should shed light onto the nature of neutrinos. At present convincing proof for the existence of sterile neutrinos specifically in the 3 + 1 scenario is lacking. Therefore more dedicated measurements are required. An exciting era of High Energy Neutrino Astrophysics has begun with the new results from IceCube giving us another window into the structure of the universe. In summary presently neutrino physics is predominately an experimentally driven field and we can expect more interesting results and surprises in the near future.

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