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Future Neutrino Experiments

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The discovery of neutrino oscillation revealed new physics beyond the standard model of particle physics. At present, the nature of neutrinos is among the most important issues in modern physics and has been widely studied. Experiments play an indispensable role in our understanding of neutrinos, establishing how small θ_{13} is, whether there is CP violation in the lepton sector, the neutrino is a Majorana or a Dirac particle, and its absolute mass. However, the accuracies of current neutrino experiments are insufficient, and a next generation of experiments with higher precision is necessary. Here, we briefly review the future neutrino experiments, including reactor, accelerator, and solar neutrino experiments, double beta decay experiments, etc.

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1. Introduction

From the Homestake solar neutrino experiment in 1968 to the current MINOS experiment at Fermi Lab, neutrino oscillation has been well established, which indicates that neutrinos have tiny masses [1, 2, 3, 4, 5, 6]. Neutrino flavor eigenstates, which are created in weak interaction processes, are superpositions of neutrino mass eigenstates:

$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i}|\nu_i\rangle \ , \tag{1.1}$$

where α denotes the lepton flavor, e, μ, or τ and, the ν_i are mass eigenstate($i = 1$, 2, or 3). From the measurements of solar and atmospheric neutrino experiments, we obtain two different mass splittings, ΔM^2_{21} and ΔM^2_{32} of three generations of neutrinos. Hence, $U^*_{\alpha i}$ is the mixing matrix from ν_1, ν_2, and ν_3 to ν_e, ν_μ, and ν_τ, which is called the PMNS matrix and can be parameterized as a multiplication of four matrices:

$$\begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta_{\rm CP}} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{i\delta_{\rm CP}} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} e^{i\delta_1} & 0 & 0 \\ 0 & e^{i\delta_2} & 0 \\ 0 & 0 & 1 \end{pmatrix} . \tag{1.2}$$

The fourth matrix is related to Majarana neutrino properties. The three mixing angles ($\theta_{\rm ij}$), one CP phase ($\delta_{\rm CP}$), and two mass splittings ($\Delta m^2_{\rm ij}$) are the neutrino oscillation parameters. Among them, mixing angle θ_{12} and smaller mass splitting ΔM^2_{21} were measured by solar neutrino experiments (e.g. Homestake [1] and SNO [2]), and confirmed by reactor neutrino experiments (KamLAND [3]). Mixing angle θ_{23} and larger mass splitting ΔM^2_{32} were measured in atmospheric (SuperK [5]) and accelerator (e.g. K2K [4] and MINOS [6]) neutrino experiments. At present the constraints on these parameters are [7]:

$$\sin^2(2\theta_{12}) = 0.87 \pm 0.03 \ , \qquad \sin^2(2\theta_{23}) > 0.92 \ , \tag{1.3}$$

$$\Delta M^2_{21} = (7.59^{+0.19}_{-0.21}) \times 10^{-5}\,{\rm eV}^2 \ , \ \ |\Delta M^2_{32}| = (2.43 \pm 0.13) \times 10^{-3}\,{\rm eV}^2 \ . \tag{1.4}$$

The values of θ_{13}, the absolute value of ΔM^2_{32} (mass hierarchy) and the CP phase $\delta_{\rm CP}$ are still unknown. From equation 1.2, we can see that the CP phase appears in the PMNS matrix together with the unknown mixing angle θ_{13}. Therefore, the study of CP phase highly depends on the measurement of θ_{13}. Furthermore, the determination of the neutrino mass hierarchy is expected to be disentangled in the next generation of long baseline accelerator neutrino experiments, if the value of θ_{13} is not too small. The current experiment limit on θ_{13} is provided by the CHOOZ experiment [8]: when assuming $\Delta M^2_{32} = 2.5 \times 10^{-3}{\rm eV}^2$, the 90% C.L. upper limit is $\sin^2(2\theta_{13}) < 0.15$. Global fitting results slightly favor a non-zero value of θ_{13}, namely $\sin^2(2\theta_{13})$=0.05 [9]. These results suggest improving the precision of the $\sin^2(2\theta_{13})$ measurement to a sensitivity of 0.01.

2. Measurements of θ_{13} in Reactor Neutrino Experiments

Currently, around the world, there are three reactor neutrino experiments with the physics goal of discovering the value of θ_{13}, Daya Bay, Double Chooz and RENO. They are all undergoing detector construction and will start data taking soon. The basic idea of measuring θ_{13} in reactor neutrino experiments is to measure the survival probability of electron-antineutrino events via near/far relative measurements:

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \approx 1 - \sin^2(2\theta_{13})\sin^2\left(\frac{\Delta m^2_{31}L}{4E}\right) - \cos^4\theta_{13}\sin^2(2\theta_{12})\sin^2\left(\frac{\Delta m^2_{21}L}{4E}\right), \tag{2.1}$$

where L and E denote detector baseline and neutrino energy, respectively. One detector is placed at the near site to monitor the flux and energy spectrum of electron-antineutrinos, whose energy is from 1.8MeV to 8MeV, emitted from the reactors. An identical detector is placed at the far site, where the first oscillation maximum occurs and is dominated by the $\sin^2(2\theta_{13})$ item in equation 2.1. In addition, the oscillation contributions from $\sin^2(2\theta_{12})$ and the mass hierarchy are negligible. Therefore, reactor neutrino experiments provide a clean measurement of θ_{13}. Compared with accelerator neutrino experiments, the event rates at the far detector can be exactly $1/r^2$ extrapolated from measured rates at the near detector, and have no neutral current background. The target for detecting anti-electron neutrinos is Gadolinium loaded liquid scintillator. The detection interaction in the target is the inverse β decay process, $\bar{\nu}_e + \mathrm{p} \rightarrow e^+ + \mathrm{n}$. The coincidence of prompt positron and delayed neutron signals, in both time and energy is a powerful background rejection. The Gd-loaded liquid scintillator improves background suppression with higher capture energy and shorter neutron capture time.

The Daya Bay reactor neutrino experiment [10] is located on the south east coast of China. After 2011, the Daya Bay nuclear power plant will be operating six nuclear cores at a total of 17.4GW thermal power. The experiment will use two near sites and one far site. Two identical anti-neutrino detectors will be placed at each near site, and four at the far site. Each anti-neutrino detector has a three-layer cylindrical structure with a 5m diameter and 5 m height. The innermost target is 20T of Gd-loaded liquid scintillator. The middle layer is 20T of liquid scintillator, which is used to capture γs that escaped from the target volume. The outermost layer is 40T of mineral oil, which shields against the radioactivity from the surroundings. These three layers are contained within stainless steel vessel and separated by acrylic vessels. For each anti-neutrino detector, 192 PMTs will be installed into the steel stank and immersed in the oil to detect optical photons. Top and bottom reflectors increase the light response uniformity of the detector and the photoelectric yield at the PMTs. At each site, the anti-neutrino detectors will be placed into a water pool and surrounded by at least 2.5m water to shield against neutrons and γs. The water pools will be instrumented with PMTs to tag cosmic muons. Above each water pool, arrays of RPC modules will be used to tag muons together with the Cherenkov detector in the water pool. The combination of muon tagging efficiency will be higher than 99.5%. It is estimated that for each anti-neutrino detector, there will be about 800 events/day at the near sites and 90 events/day at the far site.The systematic uncertainty is estimated to be 0.13% (reactor-related) and 0.38% (detector-related), while the statistical uncertainty will be around 0.2% after three years data taking. The Daya Bay experiment will start taking data with all three sites in the fall of 2012. After one year of data taking, Daya Bay will reach the sensitivity of $\sin^2(2\theta_{13})$ to 0.01. Besides the Daya Bay experiment, Double Chooz [11] and RENO [12] will start taking data in 2012 and at the end of this year, respectively. Table 1 compares the current three reactor neutrino experiments aiming to measure θ_{13}. Daya Bay is the only experiment that can reach the sensitivity of $\sin^2(2\theta_{13})$ to 0.01.

Table 1: Comparison of Double Chooz, Daya Bay and RENO.

	Double Chooz	RENO	Daya Bay
Thermal Power (GW)	8.5	16.4	17.4
Mass (Ton)	2×10	2×16	8×20
δ_{system}(%)	0.6	0.5	>0.2, <0.4
Near: Distance(m)	400	290	363, 481
Far: Distance(m)	1050	1380	1985, 1613
Near: Depth(m.w.e)	115	130	260
Far: Depth(m.w.e.)	300	460	910

3. Measurements of θ_{13} in Accelerator Neutrino Experiments

Accelerator neutrino experiments measure the appearance probability of electron-antineutrinos from a muon neutrino beam:

$$\begin{aligned} P(\nu_\mu \to \nu_e) \approx{}& \sin^2(2\theta_{13})\sin^2\theta_{23}\sin^2\left(1.27\Delta m^2_{31}\frac{L}{E}\right)+\sin^2(2\theta_{12})\cos^2\theta_{23}\sin^2\left(1.27\Delta m^2_{21}\frac{L}{E}\right) \\ &+ \sin(2\theta_{13})\sin(2\theta_{23})\sin(2\theta_{12})\sin\left(1.27\Delta m^2_{31}\frac{L}{E}\right)\sin\left(1.27\Delta m^2_{21}\frac{L}{E}\right)\cos\left(1.27\Delta m^2_{32}\frac{L}{E}\pm\delta_{\text{CP}}\right) . \end{aligned} \tag{3.1}$$

The appearance probability is not only dependent on the value of θ_{13}, but also on the values of δ_{CP} and the mass hierarchy. The most recent results come from the MINOS experiments [13]. The expected event in the far detector is 49.1±7.0(stat.)±2.7(syst.), and the observed event is 54. There is a 0.7σ excess. Assuming $\delta_{\text{CP}} = 0$, $\sin^2(2\theta_{23}) = 1$, $|\Delta m^2_{32}| = 2.43 \times 10^{-3}\text{eV}^2$, one gets $\sin^2(2\theta_{13}) < 0.12$ in the so-called normal mass hierarchy and $\sin^2(2\theta_{13}) < 0.20$ in the inverted mass hierarchy at 90% C.L.

T2K [14] and NOVA [15] are two accelerator neutrino experiments under construction which are designed to discovery the value of θ_{13}. The T2K experiment uses the high-intensity neutrino beam from J-PARC, which is a narrow band beam (2.5deg off-axis beam) and tuned at the oscillation maximum energy of ∼600MeV. T2K has two near detectors at a baseline of 280m, which are used to measure the neutrino flux and spectra. One detector is on-axis to monitor the beam intensity and direction, and the other detector is off-axis, which aims in the direction of the SuperK detector. The SuperK 50KT water cherenkov detector is the T2K far detector, which is 295km away from the beam pipe. QECC interactions dominate in the far detector: ν_l + n $\to l^-$ + p. T2K has been taking data since Jan. 2010. The beam power is about 50KW. After November 2010, the beam will be upgraded from 100KW to 0.75MW. The final goal is to accumulate 0.7KW$\times 5 \times 10^7$ second events, and reach a sensitivity of $\sin^2(2\theta_{13})$ about 0.008 at 90%CL, if the CP phase is zero.

The NOVA experiment also uses a high intensity off-axis neutrino beam, which is from the Fermi Lab NuMI beam, and will be upgraded to 0.7MW in the Fall of 2011. Its near detector is about 12m-off-axis, and the far detector is about 12km-off-axis. Both the near and far detectors are tracking liquid scintillator calorimeters. The near detector is located in Fermi Lab, and the fiducial mass is about 23T with a 1km baseline. The fiducial mass of the far detector is 15kT, which is 810km away from the beam pipe. Therefore, the NOVA experiment is sensitive to the neutrino mass hierarchy. It will start taking data in 2013, and the first run will last six years.

Besides the measurement of θ_{13}, both NOVA and T2K will improve the precision of θ_{23} measurements.

4. Solar Neutrino Experiments

Solar neutrinos detected by the previous solar neutrino experiments are mainly ^8B neutrinos due to the background in detectors and environments. Recently, various experiments (SuperK [16, 18], Borexino [19], SNO [20, 21, 22], etc.) are lowering their detector thresholds to measure lower energy solar neutrinos which have much larger fluxes and small uncertainties in the standard solar model, like neutrinos from ^7Be, the pep chain, the pp chain, etc. The SNO experiment has reduced its threshold to 3.5MeV and given a most recent ^8B flux of $\Phi_{\rm NC} = 5.14^{+0.160}_{-0.158}(\text{stat.})^{+0.132}_{-0.117}(\text{syst.})$ [22], which is consistent with the theoretical prediction of standard solar model, $\Phi_B = 5.94 \pm 0.60$. The following solar neutrino experiments will use their lower detector threshold to study of matter-enhanced oscillation further, such as vacuum-matter oscillation transitions, and matter effects in the sun and earth. Besides the study of the matter effect, solar neutrino experiments will continue to improve the precision of mixing parameters. In addition, solar neutrino experiments will give further information on solar models.

Currently, the Borexino experiment is also running with a lower energy threshold for solar neutrino detection. Unlike KamLAND, SNO. etc., it is a liquid scintillator detector which could obtain a even lower threshold to detect sub-MeV solar neutrinos. The detector has 3800m (m.w.e) overburden in LNGS and 100T fiducial mass. Its threshold is about 200KeV, with the ultra-low background environment, a few tens cpd/100t. It is the first experiment to measure ^7Be and ^8B neutrino fluxes in the same detector and has seen no obvious day/night asymmetry [19]. Borexino will continue running to measure sub-MeV solar neutrinos for measurements such as the flux of neutrinos from the pep, CNO, pp chains.

5. Neutrino Mass Measurements

Neutrino oscillation indicate that neutrinos are massive in at least one generation. However, neutrino oscillation experiments only supply the measurements of differences of neutrino mass eigenstates. The absolute scale of neutrino masses could obtained from a direct mass measurement, such as the β decay experiment, which is independent of theoretical models, and the neutrinoless double β decay ($0\nu\beta\beta$) experiment, which is sensitive to Majorana neutrinos. The basic idea of the beta decay experiment is to observe the end-point shift and the distortion of β spectrum due to the mass of the neutrino. In order to see this tiny change close to the end-point, β decay experiments need a low end-point source, a sufficiently high count rate and energy resolution, and a low background. The current limit on m_{ν_e} from the β decay measurement is released by Mainz and Troitsk experiments [23]: $m_{\nu_e} \sim 2.3$eV at 90% C.L. The KATRIN experiment is a new β decay measurement with tritium source, whose sensitivity will go down to ~ 0.2eV (90% C.L.) and 0.35eV (5σ) [24].

Double β decay is a rare process, which only happens in some even-even nuclei. Importantly, neutrinoless double β decay implies lepton number violation, when the low-mass Majorana neutrinos are emitted during the nuclear process. The $0\nu\beta\beta$ decay is strongly suppressed compared to the $2\nu\beta\beta$ process. Therefore, isotopes which have a high Q-value are preferable. The latest measurement is provided by the Heiderburg-Moscow and IGEX experiments [25, 26], $m_{\beta\beta}$ is about 0.35eV. Some $0\nu\beta\beta$ experiments, such as the GERDA experiment [27], which is planned to be merged into the MAJORANA experiment [28], will lower the limit of $m_{\beta\beta}$ to 20-40meV, which means the half life time $T^{0\nu}_{1/2}$ will be the order of 10^{27} year. This requires the experiment to have a large target mass, an extremely low background (a few counts/keV/ton/year), while also have a very good energy resolution. One uncertainty from the measured $T^{0\nu}_{1/2}$ to $m_{\beta\beta}$ is the unknown nuclear matrix element. Nuclear physics models have several nuclear matrix element values of $0\nu\beta\beta$ isotopes and some values are quite different. Since we do not have a unified nuclear matrix element model at present, several measurements with different nuclei are necessary to extract the effective Majorana neutrino mass.

6. Summary

Neutrino oscillation experiments have indicated that neutrinos have tiny masses. Now there are many experiments which plan to measure mixing parameters in the PMNS mixing matrix. We have measured oscillation parameters with solar and atmospheric neutrinos, but still do not know how small θ_{13} is. The value of θ_{13} will determine how we explore the other two unknown basic mixing parameters, the mass hierarchy and the CP phase. CP phase might help us answer one of big questions: why is there so much more matter than antimatter in the universe? In addition, several direct neutrino mass measurements are under construction. They might help us determine whether neutrinos are Dirac or Majorana particles, and to determine the neutrino mass spectrum. Furthermore, cosmology could also give the information of the total mass of three neutrino mass eigenstates by using various of observational data, such as CMB and large scale structure [29].

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