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# Future of neutrino experiments

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**Abstract.** Atmospheric, solar, reactor and accelerator neutrino oscillation experiments have measured $\Delta m^2_{12}$, $\sin^2\theta_{12}$, $|\Delta m^2_{23}|$ and $\sin^2 2\theta_{23}$. The next stage of the oscillation studies should be the observation of a finite $\sin^2 2\theta_{13}$. If a non-zero $\sin^2 2\theta_{13}$ is observed, the subsequent goals should be the observation of the CP violation and the determination sign of $\Delta m^2_{23}$. Possible future neutrino oscillation experiments that could assess these questions are discussed.

**Keyword.** Neutrino oscillations.

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## 1. Introduction

Small but finite neutrino masses are believed to be related to physics at a very high energy scale. Also the observed large neutrino mixing angles might be the hint for understanding physics at very high energies. Furthermore, the physics of neutrino masses might be related to the baryon asymmetry of the universe. Hence, it is likely that neutrino physics contributes to our deeper understanding of nature. Therefore we should try to get as much information as possible from neutrino oscillation experiments.

In the 3-flavour neutrino oscillation framework, there are three mixing angles ($\theta_{12}$, $\theta_{23}$, $\theta_{13}$), one CP phase ($\delta$), and two neutrino mass squared differences ($\Delta m^2_{12}$, $\Delta m^2_{23}$ ($=\Delta m^2_{13}$)). In the 2-flavour $\nu_\mu \to \nu_\tau$ oscillations, the oscillation probability is expressed as

$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\theta_{23} \sin^2\left(\frac{1.27\Delta m^2_{23} L}{E_\nu}\right). \qquad (1)$$

After the initial discovery of neutrino oscillations in atmospheric neutrino experiments [1,2], our understanding of neutrino masses and mixing angles has been improving significantly. Atmospheric [3,4] and long baseline accelerator neutrino experiments [5–7] have measured $\sin^2 2\theta_{23}$ and $|\Delta m^2_{23}|$. Solar neutrino experiments [8,9] and the KamLAND long baseline reactor neutrino experiment [10] have measured $\sin^2\theta_{12}$ and $\Delta m^2_{12}$. Figure 1 shows the estimated allowed regions of 2-flavour

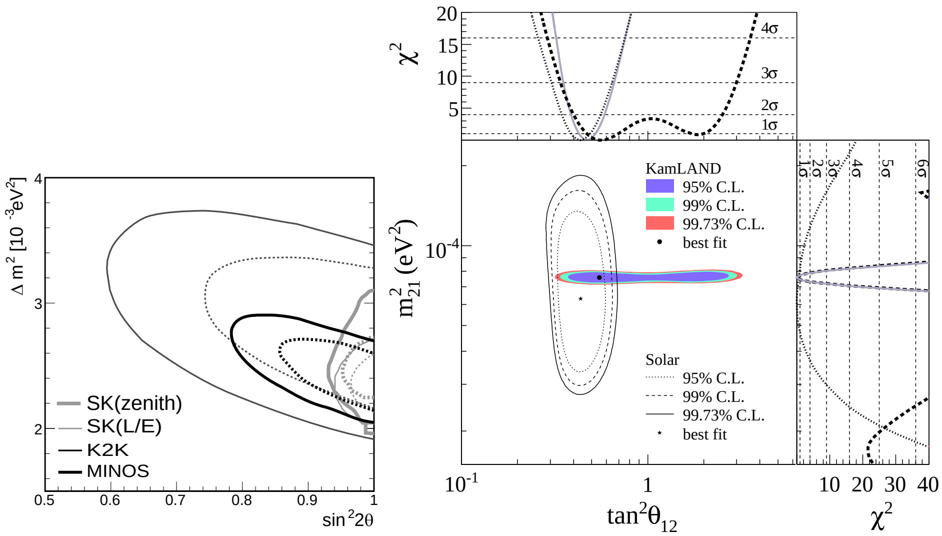


**Figure 1.** Allowed regions of 2-flavour $\nu_\mu \to \nu_\tau$ oscillation parameters from atmospheric and long baseline experiments (left), and $\nu_e \to \nu_{(\mu \text{ or } \tau)}$ parameters from solar and KamLAND experiments (right).

$\nu_\mu \to \nu_\tau$ and $\nu_e \to \nu_{(\mu \text{ or } \tau)}$ (taken from [10]) oscillation parameters from these experiments.

In addition, there was another indication for oscillations by the LSND experiment [11], which observed an excess of electron candidates in the $\bar{\nu}_\mu$ beam. Recently, the MiniBooNE Collaboration reported that MiniBooNE has not observed the expected LSND signal, excluding the 2-flavour oscillation interpretation of the LSND result at 98% CL [12]. With this result, we finally conclude that the present oscillation data are explained within the 3-flavour oscillation framework.

In this article, the future directions of the neutrino experiments are discussed. The discussion is mostly concentrated on neutrino oscillation experiments.

## 2. Search for non-zero $\theta_{13}$

### 2.1 *Present status*

Although $\theta_{23}$ and $\theta_{12}$ have already been measured, only the upper limit on the third angle ($\theta_{13}$) is known. For simplicity, we neglect the effect of the oscillations related to $\Delta m^2_{12}$. Under this approximation, there are only three oscillation parameters: $\theta_{13}$, $\theta_{23}$ and $\Delta m^2$ ($\equiv \Delta m^2_{13} = \Delta m^2_{23}$). In this case, for example, the $\nu_e \to \nu_e$ and $\nu_\mu \to \nu_e$ oscillation probabilities in vacuum can be written as

$$P(\nu_e \to \nu_e) = 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{1.27\Delta m^2_{13} L}{E_\nu}\right), \tag{2}$$

$$P(\nu_\mu \to \nu_e) = \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\left(\frac{1.27\Delta m^2_{13}L}{E_\nu}\right). \quad (3)$$

The CHOOZ experiment searched for $\bar{\nu}_e$ disappearance in the reactor $\bar{\nu}_e$ flux. The observed flux was consistent with the no-oscillation expectation. The upper limit on $\sin^2 2\theta_{13}$ was $\sim$0.15 [13].

Due to the matter effect, the resonant $\nu_\mu \to \nu_e$ conversion could occur for neutrinos passing through the Earth with their energies between 5 and 10 GeV. This effect can be observed as an excess of upward-going multi-GeV $e$-like events in atmospheric neutrino experiments. The atmospheric neutrino data from Super-Kamiokande show no evidence for such excess in the upward-going direction, constraining $\theta_{13}$ [14]. The constraint on $\theta_{13}$ from the Super-Kamiokande atmospheric neutrino experiment is less stringent than that from the reactor experiment.

K2K searched for $\nu_\mu \to \nu_e$ oscillations [15]. The number of observed candidate $\nu_e$ events was 1, while the expected number of the background events was $1.7^{+0.6}_{-0.4}$. Among the total background events, 1.3 originated from $\nu_\mu$ and the remaining 0.4 from $\nu_e$ existing in the initial beam. Thus, no evidence for an electron appearance was observed, constraining the $\theta_{13}$ parameter. The upper limit on $\sin^2 2\theta_{13}$ was 0.26(0.28) for $\Delta m^2 = 2.8(2.4) \times 10^{-3}$ eV$^2$, assuming $\sin^2 2\theta_{23} = 1.0$.

The present constraints on $\theta_{13}$ from the atmospheric and the long baseline experiments are weaker than that from the CHOOZ reactor experiment [13]. However, by combining all the information from the present neutrino oscillation experiments, a slight improvement over the constraint from the CHOOZ experiment alone has been obtained [16,17].

### 2.2 *Near future $\theta_{13}$ experiments*

In the near future, various experiments that are much more sensitive to $\theta_{13}$ than the present experiments will start taking data. They use either reactor neutrinos or accelerator neutrino beams. If a finite value of $\theta_{13}$ is observed, we understand the overall structure of the neutrino mixing matrix (except for the CP phase). Thus, $\theta_{13}$ should be measured with a high priority. Furthermore, the measurement of $\theta_{13}$ is very important for future neutrino oscillation experiments, which will be discussed in the next section.

Reactor experiments try to observe $\bar{\nu}_e$ disappearance (see eq. (2)). The fact that the present best limit has been obtained by the CHOOZ reactor experiment suggests that the reactor experiments are powerful in searching for a non-zero $\theta_{13}$. However, if $\sin^2 2\theta_{13}$ is 0.01, the expected size of the disappearance signal is at most 1%, which suggests that the next generation reactor experiments should design the experiments very carefully. Especially, the systematic error in the event rate needs to be controlled to be less than 1%. To achieve this goal, each experimental group has been carefully designing the experiment with the identical near and far detectors, optimized baseline length (1 to 2 km), deep enough locations to reduce the cosmic ray-induced backgrounds, thick enough shielding, veto counters, clean detector material and careful calibration and monitor devices. Furthermore, high enough event statistics are required. This can be achieved by the large fiducial masses (10 to 80 t), long data taking periods (a few years) and using high power nuclear reactors (about 10 to 20 GW) as the neutrino sources.

At present three reactor $\theta_{13}$ experiments (Double CHOOZ [18], Daya Bay [19] and RENO [20]) are under construction. These experiments are scheduled to start taking data around 2010. The expected sensitivities of these experiments range between 0.01 and 0.03 in $\sin^2 2\theta_{13}$. These experiments might find evidence for a non-zero $\theta_{13}$.

On the other hand, the accelerator long baseline experiments try to observe $\nu_e$ appearance. See eq. (3) for the approximate appearance probability. The T2K experiment [21] and the NOvA experiment [22] have high sensitivities to the $\nu_e$ appearance.

T2K uses a very high intensity, low energy ($E_\nu < 1$ GeV) neutrino beam produced by the 40 GeV PS in the J-PARC accelerator complex, which is under construction in JAEA, Tokai, Japan. The designed beam power is 0.75 MW. The far detector is Super-Kamiokande. The baseline length is 295 km. The neutrino energy is tuned to the maximum oscillation energy. For $\Delta m^2_{23} = 2.5 \times 10^{-3}$ eV$^2$, the maximum oscillation energy is 600 MeV. To produce high-intensity, narrow-band beam, the off-axis beam technique is used. The axis of the primary beam is displaced by 2.5° from the direction to the neutrino detector. The T2K experiment will start taking data in 2009.

NOvA is the proposed long baseline experiment in the United States. This experiment plans to use the existing NuMI beam line at Fermilab. A beam power upgrade plan to about 1 MW is under investigation. The far detector is a 15 kt fully active, finely segmented liquid scintillator detector. The baseline length is 810 km. In order to get the high flux at the oscillation maximum, this experiment also uses the off-axis technique. The peak neutrino energy is about 2 GeV. The NOvA experiment is expected to start in the early 2010's.

These experiments have similar sensitivities in $\sin^2 2\theta_{13}$. Assuming five years of data taking with the planned beam intensities, these experiments can find clear evidence for a non-zero $\theta_{13}$, if the true value of $\sin^2 2\theta_{13}$ is larger than $\sim 0.02$. If there is no evidence for a non-zero $\theta_{13}$, they can set the upper limit of $\sim 0.01$ on $\sin^2 2\theta_{13}$. The sensitivities of these long baseline experiments on $\sin^2 2\theta_{13}$ are similar to or slightly better than the next generation reactor $\theta_{13}$ experiments.

Finally it should be mentioned that these long baseline experiments can measure $|\Delta m^2_{23}|$ and $\sin^2 2\theta_{23}$ precisely. It is especially interesting if these experiments could find evidence for a non-maximal $\sin^2 2\theta_{23}$, since these experiments have the approximate sensitivities of 0.01 in $\sin^2 2\theta_{23}$.

## 3. Beyond $\theta_{13}$

We assume that the next generation long baseline and reactor experiments will observe evidence for a non-zero $\theta_{13}$, suggesting $\sin^2 2\theta_{13}$ to be larger than $\sim$0.01. In this case, we know the approximate values of the three mixing angles. However, we believe that this should not be the end of the neutrino oscillation studies. In fact, there are still important and unknown neutrino oscillation parameters. One is the CP phase. According to the leptogenesis scenario [23], the seed of the baryon

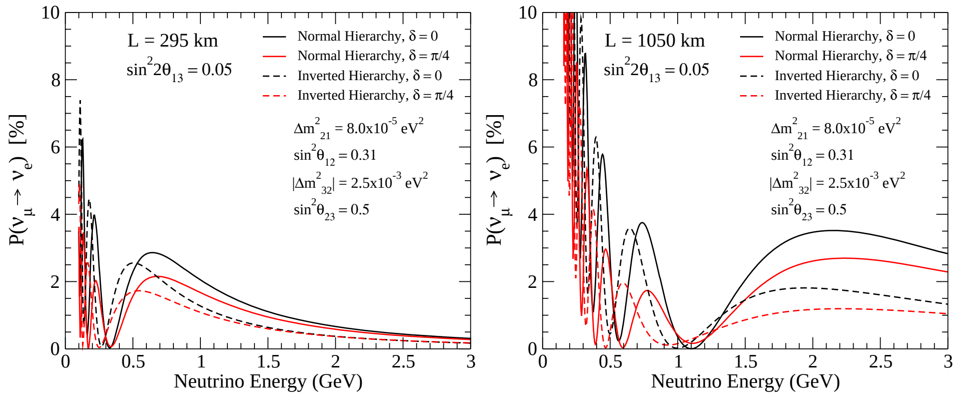


**Figure 2.** Energy dependence of the oscillation probabilities for $\sin^2 2\theta_{13} = 0.05$, for normal (solid lines) and inverted (dashed lines) mass hierarchies, and for $\delta = 0$ (black) and $\pi/4$ (red). The left and the right panels are for detectors at 295 km and 1050 km, respectively.

asymmetry in the universe is generated from the CP violating decay of the heavy Majorana particles of the see-saw mechanism. Therefore, it is generally believed that the measurement of the CP violation in the neutrino sector is a very important step forward for understanding the baryon asymmetry in the universe. In addition, we do not know whether the $\nu_3$ mass eigenstate is the heaviest or the lightest. This is also an important question to be addressed experimentally.

If $\theta_{13}$ is non-zero, future large-scale long-baseline experiments can address these questions. Various possibilities for these experiments have been studied. One study has been carried out in the United States, which assumed a 1300 km baseline between Fermilab and DUSEL at Homestake [24]. The beam power could be as high as 2 MW. The detectors used in this study are a 300 kt water Cherenkov detector and a 100 kt liquid argon detector.

The other possibility for such experiments could be the phase-2 of the T2K project [21]. The CP violation phase can be measured by observing the difference in the neutrino oscillation probabilities between $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$. To observe this effect, a huge detector (1 Mt Hyper-Kamiokande detector), and a beam power upgrade of J-PARC should be required. Due to the relatively short baseline length of 295 km, the mass hierarchy may not be determined in this experiment as understood from figure 2 (left). Figure 2 shows the energy dependence of the $P(\nu_\mu \to \nu_e)$ oscillation probabilities at 295 and 1050 km. The T2K experiment uses an off-axis beam. It is noticed that, with the present T2K beam-line configuration, the beam is simultaneously available in Kamioka (which is 295 km away from the target) and Korea (which is more than 1000 km away from the target).

The matter effect is bigger for longer baseline lengths (higher neutrino energies) as seen in figure 2. The matter effect dominates over the CP effect at the first oscillation maximum at 1050 km, while the CP effect is larger than (or comparable to) the matter effect at 295 km. It is noticed from figure 2 that the size of the CP effects in $P(\nu_\mu \to \nu_e)$ (and $P(\bar{\nu}_\mu \to \bar{\nu}_e)$) become larger by a factor of about 3 in the second oscillation maximum compared with the first oscillation maximum. These

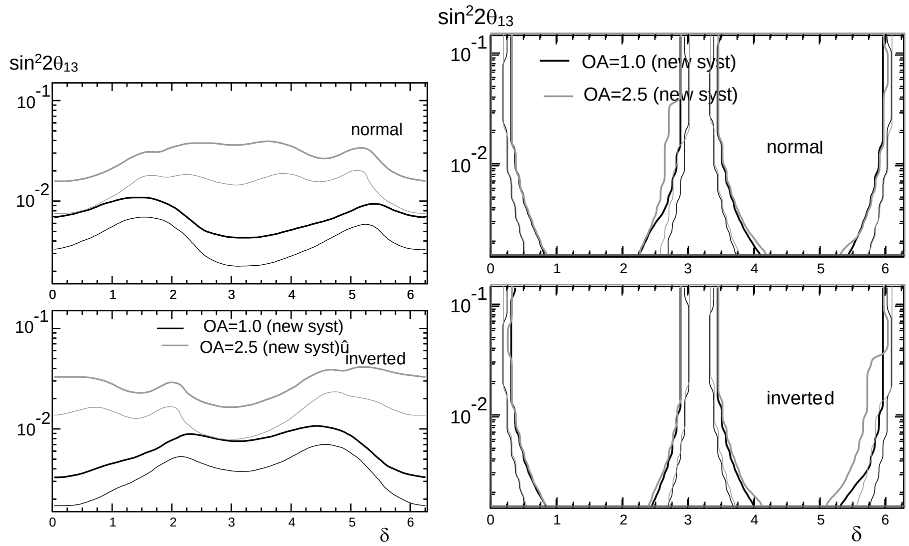


**Figure 3.** Two (thin lines) and three (thick lines) $\sigma$ sensitivities to the mass hierarchy (left) and the CP violation (right) for 0.27 Mt detectors at Kamioka (295 km) and Korea (1050 km). The off-axis angle is 2.5° for the Kamioka detector, and either 2.5 (gray) or 1.0 (black) degrees for the Korean detector. The detector exposure is assumed to be five years for both the neutrino and antineutrino beam. Various systematic errors are taken into account.

features suggest that the mass hierarchy and the CP violation can be measured by very long baseline experiments (possibly with two detectors with different baseline lengths [25]).

Detailed $\chi^2$ analysis was carried out taking into account various detector effects, such as the background contamination, the detection efficiency, and their systematic errors. Figure 3 shows results from one of the recent studies assuming the upgraded J-PARC beam of 1.66 MW and detectors at Kamioka (295 km) and Korea (1050 km assumed), both with 0.27 Mt fiducial mass [26]. Figure 4 shows results from another study for a long baseline experiment between Fermilab and Homestake [24]. It is clear that the CP violation and mass hierarchy can be studied by these future experiments, if $\sin^2 2\theta_{13}$ is larger than $\sim$0.01.

### 3.1 *Some remarks*

While accelerator-based long baseline experiments have been discussed so far, atmospheric neutrino experiments could study these physics as well. The neutrino flight length ranges up to 12800 km. Therefore, a large matter resonance is expected to occur for neutrinos (antineutrinos) in the energy range of 5 to 10 GeV, if the mass hierarchy is normal (inverted). There have been studies carried out for a large water Cherenkov detector [27,28] and for a large iron calorimeter experiment (INO)

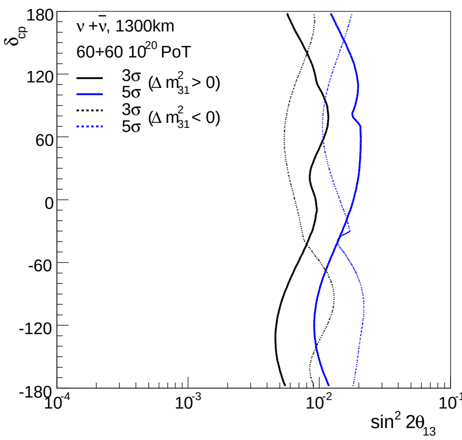


**Figure 4.** Three (black lines) and five (blue lines) $\sigma$ sensitivities to the mass hierarchy (left) and the CP violation (right) for a long baseline experiment between Fermilab and Homestake, where the baseline length is 1300 km. A 300 kt water Cherenkov detector and a wide-band beam with $60\times10^{20}$ protons-on-target for the neutrino and antineutrino beams are assumed. 10% systematic errors for the background are assumed.

[29]. In a water Cherenkov experiment, a resonant electron appearance signal can mainly be measured, while in an iron calorimeter experiment, a change in the muon disappearance probability at the resonance energy region can be measured. In a magnetized iron calorimeter experiment, the charge of the muon can be measured. Therefore, it is possible to discriminate the mass hierarchy. On the other hand, in a water Cherenkov detector, it is possible to know if the resonant appearance is due to $\nu_e$ or $\bar{\nu}_e$ by studying the $\mathrm{d}\sigma/\mathrm{d}y$ distribution, where $y$ is $(E_\nu - E_{\text{lepton}})/E_\nu$. Detailed studies showed that if the total exposure exceeds approximately 1 Mt·yr and if $\sin^2 2\theta_{13}$ is larger than about 0.05, it is possible to determine the mass hierarchy [27–29].

If the true value of $\sin^2 2\theta_{13}$ turned out to be smaller than 0.01, it might be required to have a new strategy, since the next generation $\theta_{13}$ experiments might not be able to find any evidence for a non-zero $\theta_{13}$, and hence it might not be able to optimize the experiment that measures the CP violation and the mass hierarchy. Furthermore, the future superbeam long baseline experiments might not have high enough sensitivities due to the intrinsic contamination of the $\nu_e$ flux in the beam, which is approximately 0.5 to 1%. Therefore, the strategy for the neutrino oscillation experiments in this case is not clear yet. However, technologically, it is known that there exist two possible experiments that study $\theta_{13}$, CP violation and mass hierarchy for a very small $\theta_{13}$. They are experiments with a beta beam and a neutrino factory based on a muon storage ring. In these experiments either accelerated beta nuclei (such as $^6$He) or muons are used as the neutrino source. As a result, the beam is very pure. Many sensitivity studies have been carried out. Figure 5 shows one of the study results [30]. It is clear that experiments with the neutrino factory based on the muon storage ring can explore the CP violation and

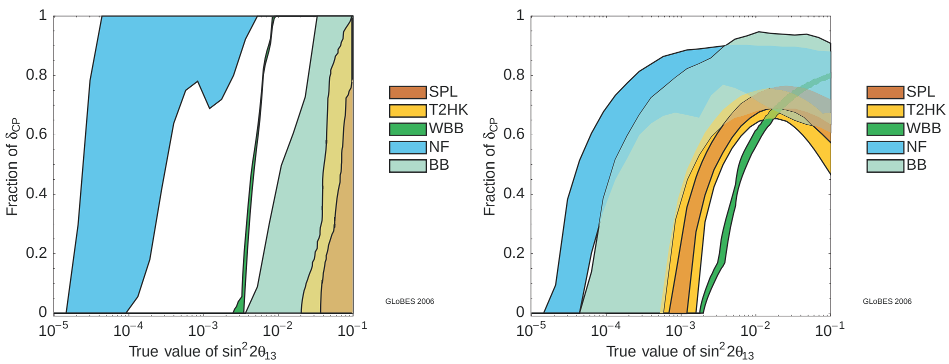


**Figure 5.** Sensitivities to the mass hierarchy (left) and the CP violation (right) for a neutrino factory (NF) and beta beam (BB).

the mass hierarchy even if $\sin^2 2\theta_{13}$ is very small. On the contrary, the sensitivity of the beta beam to the mass hierarchy is limited due to the relatively low neutrino energies.

While the future long baseline experiments are likely to address many of the important questions related to neutrino masses and mixing angles, it is also clear that these experiments cannot address all of the important, neutrino-related questions. Different types of experiments are required to address the question on the absolute neutrino masses. Furthermore, in order for the see-saw mechanism to work, neutrinos must be Majorana particles. Neutrino-less double beta decay can address these fundamental questions. (We also notice the importance of tritium beta decay experiments that can measure the neutrino mass kinematically [31].) Therefore, various double beta decay experiments have been designed and some of them are under construction. The next generation double beta decay experiments are sensitive to the inverted mass hierarchy. In order to explore the normal mass hierarchy, the sensitivity of the experiments still needs to be improved substantially. For example, see [32] for more details of the double beta decay experiments.

## 4. Conclusions

The studies of the atmospheric, solar, reactor and accelerator neutrinos led to detailed understanding of the dominant $\nu_\mu \rightarrow \nu_\tau$ and $\nu_e \rightarrow \nu_{(\nu_\mu \text{ or } \nu_\tau)}$ oscillations. However, various parameters such as the sign of $\Delta m^2_{23}$, $\theta_{13}$, and the CP phase $\delta$ are unknown. Therefore, future experiments should measure these unknown parameters. The next generation neutrino oscillation experiments can find evidence for a non-zero $\theta_{13}$, if $\sin^2 2\theta_{13}$ is larger than 0.01. The subsequent major goals are the discovery of the CP violation, the determination of the mass hierarchy and the observation of the neutrino-less double beta decays. The world community has been working hard for the best strategy for these measurements. We hope that future neutrino experiments give us essential information for our deeper understanding of nature.

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