PRAMANA — journal of physics
© Indian Academy of Sciences
Vol. 67, No. 4
October 2006
pp. 639–653

Results from solar, atmospheric and K2K experiments and future possibilities with T2K

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Abstract. Recent results from solar, reactor, atmospheric and long baseline (K2K) experiments are discussed. With the improved data statistics and analyses, our knowledge on the neutrino masses and mixing angles are steadily improving. T2K is the next generation neutrino oscillation experiment between J-PARC in Tokai and Super-Kamiokande. This experiment will start in 2009. This experiment is expected to improve the current knowledge on the neutrino masses and mixings substantially.

Keywords. Neutrino; neutrino oscillation.

PACS No. 14.60.Pq

1. Introduction

Studies of the neutrinos have played an essential role in the understanding of elementary particle physics. Physics of the neutrino masses and mixing angles are believed to be related to physics in the very high-energy scale [1,2], probably physics at the grand unification scale [3,4]. Furthermore, measuring the CP-violation phase in the neutrino sector is considered to be an essential step towards understanding the baryon asymmetry in the Universe [5]. Because of these reasons, there are many experiments that study neutrino oscillations using various neutrino sources, and various possibilities are discussed for future neutrino oscillation experiments.

Since there are three neutrino flavors, there must be three mixing angles (which are called θ_{12}, θ_{23} and θ_{13}) and three neutrino mass squared differences (which are called Δm^2_{12}, Δm^2_{23} and Δm^2_{13}). Among the three Δm^2_{ij}'s, only two are independent. Among the three mixing angles, θ_{13} is known to be small, while the other two angles are large. This fact, together with the hierarchy in Δm^2 ($\Delta m^2_{23} \gg \Delta m^2_{12}$), allows us to interpret the present data assuming 2-flavor oscillations to a good accuracy.

In this report, we discuss the present understanding of the neutrino masses and mixing angles based on results from solar, reactor, atmospheric and K2K neutrino experiments. We also discuss future possibilities with T2K. T2K is the next generation long baseline neutrino oscillation experiment between the J-PARC accelerator

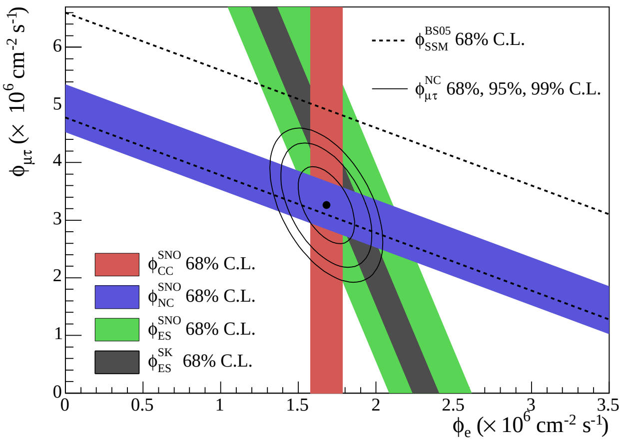

Figure 1. Constraints on ν_e and $\nu_\mu + \nu_\tau$ fluxes obtained by the SNO NC, CC and ES measurements, together with the high-statistics Super-K ES measurement.

and the Super-Kamiokande detector. We wrote this paper based on the presentations at the conference. However, the results on the detection of tau neutrino interactions are updated, since the results were finalized soon after the conference.

2. Solar neutrinos

The missing solar neutrino problem has been solved by neutrino oscillations. At present, one of the important goals is the precise determination of the solar neutrino oscillation parameters.

Recently, SNO published the final salt-phase data based on 391 days of exposure of the detector [6]. The salt phase of SNO has enhanced sensitivity to the neutral current (NC; $\nu_x + d \to \nu_x + p + n$, and n is detected by $n +^{35}\mathrm{Cl} \to^{36}\mathrm{Cl} + \gamma' s (\Sigma_{E\gamma} = 8.6$ MeV) interactions in addition to the measurements of the charged current (CC; $\nu + d \to e^- + p + p$) and elastic scattering (ES; $\nu_x + e^- \to \nu_x + e^-$) interactions. The measured CC/NC flux ratio was $0.340 \pm 0.023^{+0.029}_{-0.031}$, which is completely consistent with, but slightly higher than the previous central value $(0.306 \pm 0.026 \pm 0.024)$ [7]. Figure 1 (taken from [6]) shows the constraint on the ν_e and $(\nu_\mu + \nu_\tau)$ fluxes from SNO and Super-Kamiokande (Super-K) [8]. All the data are consistently explained within the standard oscillation framework.

The day–night asymmetry was also measured in the salt phase. Defining the asymmetry as $A = 2(\phi_{\mathrm{N}} - \phi_{\mathrm{D}})/(\phi_{\mathrm{N}} + \phi_{\mathrm{D}})$ and assuming that the asymmetry is zero for NC events, the asymmetry in the salt-phase data [6] was $A_{\mathrm{CC}} = -0.015 \pm 0.058(\mathrm{stat.}) \pm 0.027(\mathrm{syst.})$. If we combine the SNO pure D_2O data [9] with the SNO salt phase data, the asymmetry is $A_{\mathrm{CC}} = +0.037 \pm 0.040$. Super-K measured the asymmetry in the ES events [8]. It was $A_{\mathrm{ES}} = +0.021 \pm 0.020(\mathrm{stat.})^{+0.012}_{-0.013}(\mathrm{syst.})$. The asymmetry measured by ES is expected to be smaller than the asymmetry measured by CC interactions due to the presence of ν_μ and ν_τ interactions. Assuming the present best-fit oscillation parameters, the expected asymmetry measured by ES is smaller than the asymmetry measured by CC interactions by a factor of 1.55. Using this factor, it is possible to combine the CC and ES data; the combined asymmetry in the ν_e flux is $A_{\rm CC} = +0.035 \pm 0.027(\text{stat.} + \text{syst.})$. The observed asymmetry is still not statistically significant. However, we remark that the observed asymmetry is consistent with the expected asymmetry (+0.027) for the best-fit oscillation parameters.

Finally, we remark that the Super-K-II solar neutrino data have been analyzed. The analysis threshold is higher due to lower photo-cathode coverage in the Super-K-II detector. Nevertheless, the data are consistent with the Super-K-I data. At the conference in January 2006, the Super-Kamiokande detector was in the middle of the work toward the full recovery. It is expected that the experiment will resume in the summer of 2006.

2.1 *KamLAND reactor experiment*

KamLAND is a long baseline reactor neutrino experiment, which uses 1 kton of ultra-pure liquid scintillator. It detects anti-electron neutrinos from many reactors in Japan. The mean baseline length is 180 km. Therefore, this experiment is sensitive to neutrino oscillations with Δm^2_{12} larger than 10^{-5} eV^2.

About 70 GW (thermal power) is generated by the reactors at 130–220 km from KamLAND. The expected number of events without neutrino oscillation was 365.2 during 766 ton·year of the exposure. The observed number of candidate events was 258. Among them 17.8 events are expected from non-neutrino background [10]. It is evident that the number of observed neutrinos is much fewer than expected. In addition, KamLAND observed the energy spectrum of these neutrinos [10], which shows a clear distortion of the spectrum and can be fitted well by neutrino oscillations as shown in figure 2 (taken from [10]).

2.2 Δm^2_{12} *and* $\sin^2 2\theta_{12}$ *measurement*

Figure 3 (taken from [6]) shows the allowed oscillation parameter regions [6] from the solar neutrino experiments and the KamLAND reactor experiment [10]. The present allowed mixing angle is consistent with, but slightly larger than the previous one due to the slightly larger NC/CC ratio in the most recent SNO data. Since the NC/CC measurement by SNO approximately corresponds to the measurement of $\sin^2\theta_{12}$, the solar neutrino data strongly constrain the mixing angle. On the other hand, the measured energy spectrum by KamLAND strongly constrain the Δm^2_{12} value. By combining these information, the solar oscillation parameters are accurately measured. In the near future, improved statistics from KamLAND reactor neutrino measurement and the improved NC/CC ratio measurement by the ^{3}He counterphase of the SNO experiment will further improve the Δm^2_{12} and $\sin^2 2\theta_{12}$ determination.

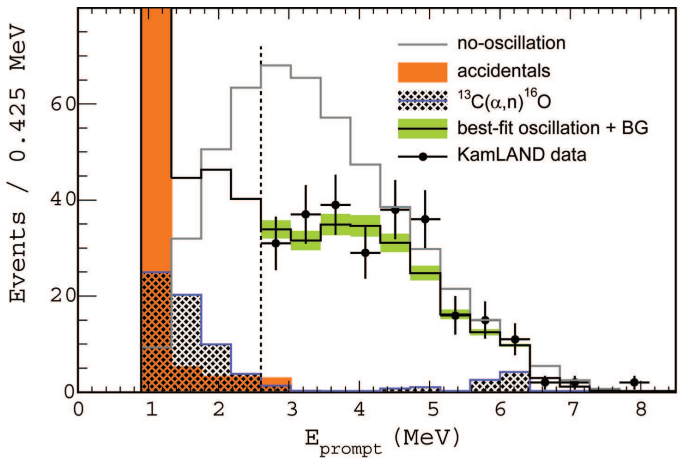

Figure 2. Observed energy spectrum of the reactor anti-electron–neutrino interactions observed in KamLAND is compared with the expected spectrum with and without neutrino oscillations. The estimated background events are also shown. The dashed line shows the threshold of the analysis (2.6 MeV).

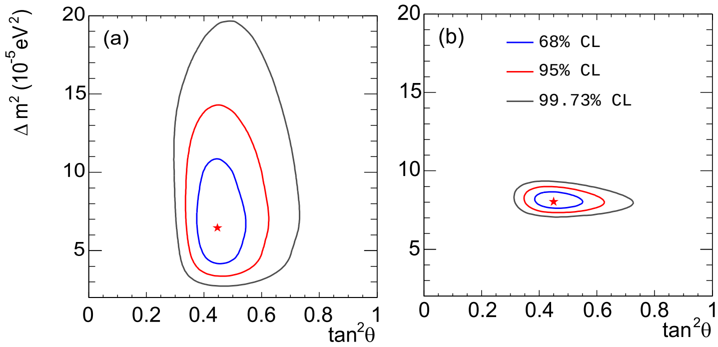

Figure 3. 68, 95 and 99.73% CL allowed parameter regions of oscillations by (**a**) solar neutrino experiments and (**b**) solar and KamLAND experiments.

3. Atmospheric neutrinos

Since the discovery of neutrino oscillations [11] (see also [12] for the earlier indication), many results from atmospheric neutrino experiments have been contributing to more detailed understanding of neutrino oscillations. Figure 4 (taken from [13]) shows the allowed parameter regions of neutrino oscillations from Super-K [14,15], Soudan-2 [13] and MACRO [16]. In addition, new measurement of the atmospheric neutrinos by the MINOS experiment was reported in this conference [17,18].

Super-K has published a paper on the full analysis of the Super-K-I data [14]. More recently, Super-K has improved the oscillation analysis using a finer energy binning. In [14], the number of bins used in the oscillation analysis was 170. In the newer analysis, the number of bins is increased to 370. The binning is finer mostly

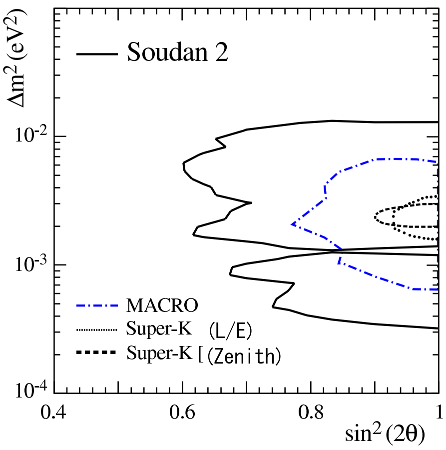

Figure 4. Allowed $(\Delta m^2_{23}, \sin^2 2\theta_{23})$ regions from Super-K (both the zenith-angle and L/E analyses), Soudan-2 and MACRO.

in the multi-GeV energy range. With these finer binning, the sensitivity to Δm^2_{23} is improved. In addition, Super-K-II data of 39 kton·yr (627 days of exposure of the Super-K detector) are available. Super-K-I and Super-K-II data have various differences in the detector resolution and systematics. Therefore, Super-K treated the Super-K-I and Super-K-II data in an independent binning. Thus the total number of bins is 740. With the new analysis, the neutrino oscillation parameters are strongly constrained as shown in figure 5. 90% CL allowed parameter region is constrained to be $\sin^2 2\theta_{23} > 0.93$ and $2.1 < \Delta m^2_{23} < 3.0 \times 10^{-3}$ eV^2.

Super-K carried out a L/E analysis based on high L/E resolution events. The L/E distribution in Super-K-I [15] showed a dip that corresponds to the first oscillation minimum. The neutrino decay [19] and decoherence [20] models were excluded at more than three standard deviations. However, the statistical significance for the dip was still statistically limited, and therefore it is desirable to have more data in order to improve the statistical significance. Figure 6 (left) shows the L/E distributions from Super-K-I and Super-K-II. The dip structure is clearly seen. The distribution is used to compare the oscillation and other hypotheses. The neutrino decay and decoherence models are disfavored at 4.4 and 4.8 standard deviations, respectively. The allowed oscillation parameter region is also constrained strongly as shown in figure 6 (right).

Super-K has finalized the analysis of tau neutrinos, which are generated by $\nu_\mu \rightarrow \nu_\tau$ oscillations. First, FC events with $E_{\rm vis} > 1.33$ GeV with the most energetic particle (Cherenkov ring) being e-like are selected. Next, maximum likelihood and neural network methods with a carefully selected set of kinematical variables, which are common to both analyses, are used to select τ-like events. Finally, the zenith angle distribution for τ-like events was fitted with the CC ν_τ signal and the other atmospheric neutrino (i.e., background) events. Since ν_τ are generated by neutrino oscillations, CC ν_τ events are expected to be upward-going only. Figure 7 shows the zenith angle distributions for candidate tau events. The excess of upward-going events is seen above the expected background from CC $(\nu_\mu + \nu_e)$ plus NC events.

SK-I + SK-II

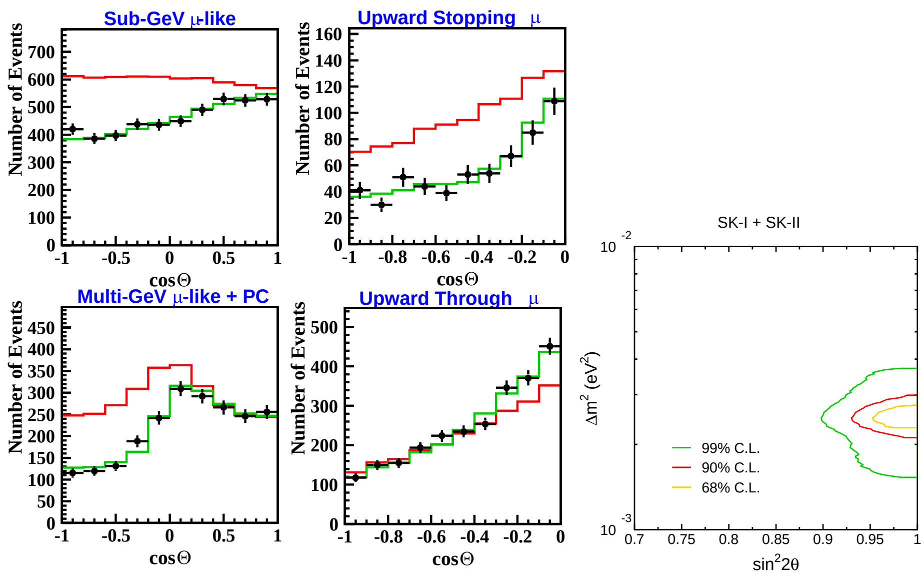

Figure 5. Left: Zenith angle distributions for some sub-samples observed in Super-K-I and Super-K-II (1489 and 627 days, preliminary). For the display purpose, the Super-K-I and Super-K-II data for each sub-sample are combined into one plot. Right: Allowed oscillation parameter regions from the zenith-angle analysis of the Super-K-I and Super-K-II data (preliminary).

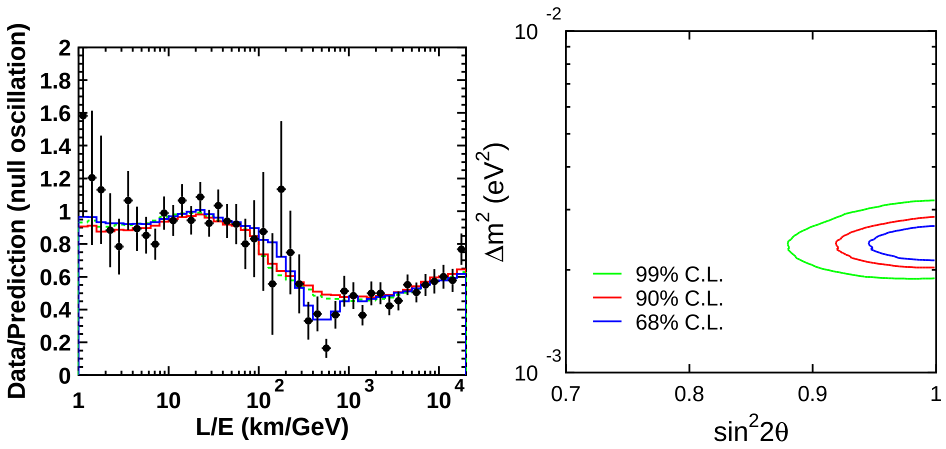

Figure 6. Left: L/E distributions observed in Super-K-I and Super-K-II (1489 and 627 days, preliminary). Right: Allowed oscillation parameter regions from the L/E analysis of the Super-K-I and Super-K-II data (preliminary).

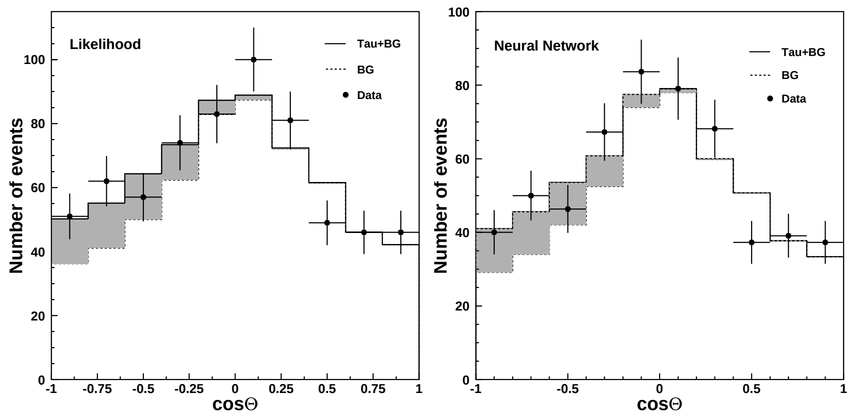

Figure 7. Zenith angle distributions of the candidate tau events observed in Super-K-I by the likelihood (left) and neural network (right) methods.

The estimated numbers of tau interactions in 92 kton·yr exposure of the detector are $138 \pm 48(\text{stat.})^{+15}_{-32}(\text{syst.})$ and $134 \pm 48(\text{stat.})^{+16}_{-27}(\text{syst.})$ from the maximum likelihood and neural network methods, respectively. The systematic errors represent the errors due to uncertainties in the oscillation parameters and those that are related to the up–down asymmetry. The expected number of tau events is 78 ± 26(syst.). The systematic error in the expected number includes all the systematic errors that are related to the overall normalization. The observed and expected number of events agree within the errors. Zero tau neutrino interaction is excluded at the 2.4σ level [21].

All these measurements suggest that the observed atmospheric neutrino data are completely consistent with $\nu_\mu \to \nu_\tau$ oscillations.

Finally, we mention that Super-K has searched for sub-dominant oscillation effects in atmospheric neutrinos. To date, no evidence for such effects has been observed [22].

4. K2K

It is generally non-trivial for atmospheric neutrino experiments to estimate the Δm^2_{23} value precisely, since each event has uncertainties in both the reconstructed L_ν and E_ν values. On the other hand, long baseline experiments have only one neutrino flight length. Therefore, in principle, it is much easier for a long baseline neutrino oscillation experiment to estimate the Δm^2_{23} value accurately.

K2K is the first long baseline neutrino oscillation experiment. Neutrinos are produced using a 12 GeV proton beam at KEK. These neutrinos are detected in Super-Kamiokande, which is 250 km distant from the neutrino production point. The mean neutrino energy is about 1.3 GeV. The estimated Δm^2_{23} value from the atmospheric neutrino experiments suggests that the maximum oscillation effect should occur for neutrinos with energies less than 1 GeV at a flight length of 250 km. Therefore, K2K studied the energy-dependent deficit of muon neutrino events.

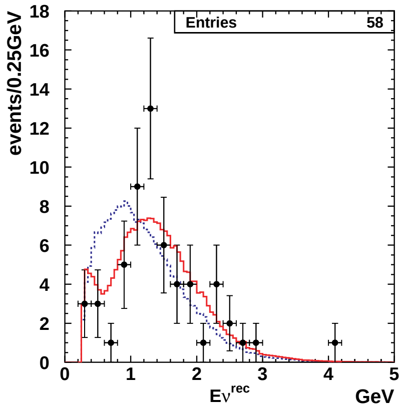

Figure 8. Reconstructed neutrino energy spectrum in K2K using 58 single-ring μ-like events. The dotted and solid histograms show the predicted spectrum for no oscillation and $\nu_\mu \rightarrow \nu_\tau$ oscillations. The histograms are normalized by the number of observed events.

During the data taking period between 1999 and 2004, data equivalent to 9.2×10^{19} protons on target (about 90% of the total protons on target requested in the proposal) were analyzed. K2K [23] observed 112 neutrino events in the far detector (Super-Kamiokande), while the expected number of events were $158.1^{+9.2}_{-8.6}$ for no oscillations [23]. The probability that the observed deficit could be due to a statistical fluctuation is estimated to be 0.06%. In addition, K2K studied the neutrino energy distribution using 58 single-ring μ-like events. It is possible to reconstruct the neutrino energy assuming two-body kinematics, i.e., quasi-elastic scattering. Figure 8 shows the reconstructed neutrino energy spectrum. A deficit of events is observed between 0.5 and 1.0 GeV. The probability that the observed energy spectrum is consistent with the no-oscillation expectation is 0.42%. The observed energy spectrum also indicates that the neutrino disappearance probability obeys sinusoidal function as predicted by neutrino oscillations. These observations are consistent with $\nu_\mu \rightarrow \nu_\tau$ oscillations.

The allowed oscillation parameter region was estimated using the number of observed events and the reconstructed neutrino energy spectrum. The allowed parameter region is shown in figure 9. If the unphysical region ($\sin^2 2\theta_{23} > 1.0$) is included in the analysis, the best-fit point is found at $\sin^2 2\theta_{23} = 1.19$. (This is mostly due to the larger energy spectrum distortion than expected.) However, with the present statistics, the probability of finding best-fit point at or above $\sin^2 2\theta_{23} = 1.19$ is estimated to be 26%. Therefore, the best-fit $\sin^2 2\theta_{23}$ in the unphysical region is likely to be due to a statistical fluctuation. The allowed region from K2K is consistent with those from the atmospheric neutrino experiments. It should be noted that the allowed Δm^2_{23} region from K2K is as small as that from the Super-Kamiokande atmospheric neutrino data, while the statistics of the K2K data are about 1% of the Super-Kamiokande atmospheric neutrino data [24].

K2K searched for $\nu_\mu \rightarrow \nu_e$ oscillations as well [26]. The number of observed candidate ν_e events was 1, while the expected background was $1.7^{+0.6}_{-0.4}$. Among the

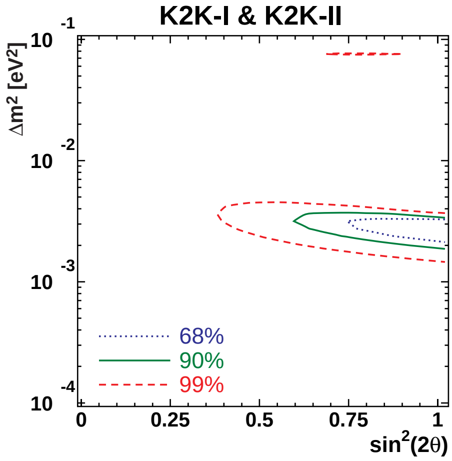

Figure 9. 68, 90 and 99% CL allowed regions of oscillation parameters from the K2K experiment.

total background events, 1.3 are originated from ν_μ and the remaining 0.4 are from ν_e in the initial beam. Thus, no evidence for electron appearance was observed, constraining the θ_{13} parameter. The limit was $\sin^2 2\theta_{13} > 0.26$ for $\Delta m^2 = 2.8 \times 10^{-3}$ eV^2, assuming $\sin^2 2\theta_{23} = 1.0$. Because of the small statistics of the data, the present constraint on θ_{13} is weaker than that from CHOOZ [27].

5. Future possibilities with T2K

Although the atmospheric neutrino and K2K results give convincing evidence for neutrino oscillations, there are several open questions. The measurement of Δm^2_{23} and $\sin^2 2\theta_{23}$ by the present experiments is not very accurate. In addition, θ_{13}, the CP-phase δ and the sign of Δm^2_{23} are not known. Future long baseline neutrino oscillation experiments should address these issues.

T2K [28] is the next generation neutrino oscillation experiment. T2K will use a very high intensity, low energy ($E_\nu < 1$ GeV) neutrino beam produced by the 50 GeV PS (40 GeV in the initial phase) in the J-PARC proton accelerator complex, which is under construction in JAEA at Tokai in Japan. The first proton beam will be available in 2008. The T2K experiment will start in 2009. The baseline length is 295 km. The main goals of the first phase of the T2K experiment are the observation of non-zero $\sin^2 2\theta_{13}$ and the precise measurement of $\sin^2 2\theta_{23}$ and Δm^2_{23}. If the true $\sin^2 2\theta_{13}$ is within 1/10 to 1/20 of the present reactor limit [27], this experiment should be able to detect non-zero θ_{13}. Furthermore, it will be possible for this experiment to measure $\sin^2 2\theta_{23}$ and Δm^2_{23} within an accuracy of 1% and a few per cent, respectively.

The neutrino energy will be tuned to that of the first oscillation maximum. For $\Delta m^2_{23} = 2.5 \times 10^{-3}$ eV^2, it is 600 MeV. To produce high intensity, narrow band beam below 1 GeV, the off-axis beam technique will be used. The axis of the

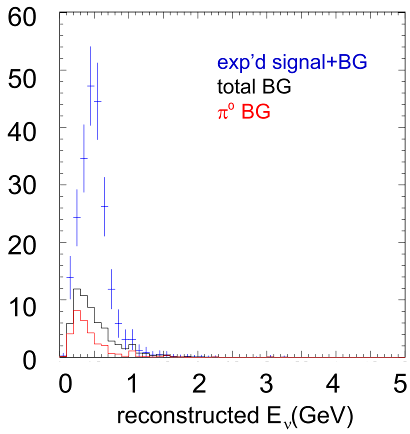

Figure 10. Expected electron appearance signal in T2K after five years of operation. The expected background events are also shown. $\sin^2 2\theta_{13} = 0.10$, $\Delta m^2 = 2.5 \times 10^{-3}$ eV^2 and $\sin^2 2\theta_{23}$=1.0 are assumed.

primary beam is displaced by a few degrees from the direction to the neutrino detector. Due to the two-body decay kinematics of pions, the energy of neutrinos that pass through the detector is low and almost independent of the pion energy spectrum. The neutrino energy can be adjusted by choosing the angle between the pion beam direction and the direction to the detector (off-axis angle). Assuming no oscillation, the expected number of events per year, which is equivalent to 10^{21} protons on target, are 3200 and 1100 for 2° and 3° off-axis beams, respectively.

The JPARC neutrino beam will have a small ν_e contamination (0.4% at the energy of the peak flux). Furthermore, the ν_e appearance signal is maximized by tuning the neutrino energy at its oscillation maximum. Thus, this experiment has a high sensitivity to θ_{13}. The appearance signal should be searched for in the single-ring e-like events. The main background processes are contamination of ν_e in the beam and NC (mostly π^0) events. Special cuts have been developed to reject these NC events (see [28] for details). Figure 10 shows the expected electron appearance signal for $\sin^2 2\theta_{13} = 0.10$, $\Delta m^2 = 2.5 \times 10^{-3}$ eV^2 and $\sin^2 2\theta_{23} = 1.0$. This experiment is sensitive to $\sin^2 2\theta_{13}$ below 0.01.

5.1 *T2K phase-II*

There are now intense studies of designing experiments that detect CP-violation effect in the neutrino sector. CP-violation in the neutrino sector is considered to be the key to understand the baryon asymmetry of the Universe [5], and therefore is very important. The CP-violating phase is currently unknown and is expected to be observable if Δm^2_{12} and Δm^2_{23} are close enough and if the three mixing angles are not small.

One such example is the Phase-2 of the T2K project. The $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillation probabilities depend on the CP-phase δ as shown in figure 11 (left).

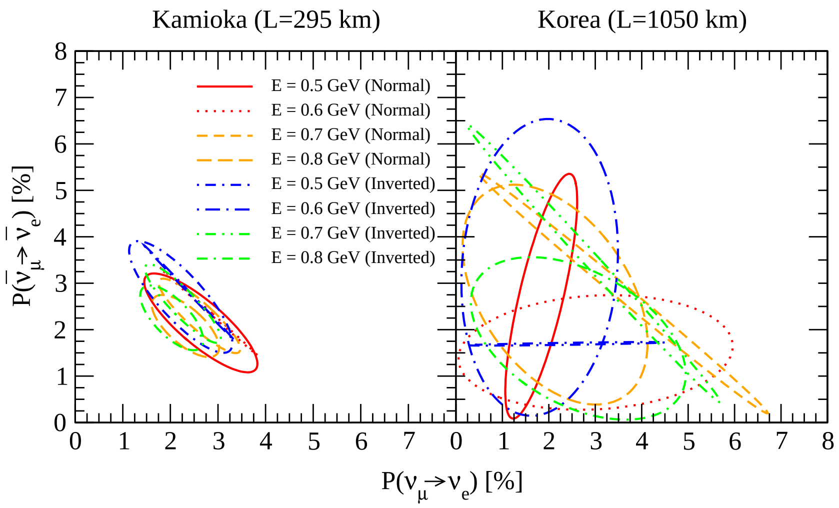

Figure 11. Energy dependences of the oscillation probabilities for $\sin^2 2\theta_{13} = 0.05$ are represented by plotting ellipses (which results as δ is varied from 0 to 2π) in bi-probability space for various neutrino energies from 0.5 to 0.8 GeV. Other mixing parameters are fixed as explained in the text. The left and the right panels are for detectors in Kamioka and in Korea, respectively.

Thus, 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 Mton Hyper-Kamiokande detector), a very high intensity proton accelerator (4 MW beam power) and about eight years of operation (two years with the neutrino beam and six years with the anti-neutrino beam) will be required [28]. The sensitivity of the experiment will be discussed in the next section. The preliminary design for Hyper-Kamiokande is in progress.

5.2 *New possibilities with a detector in Korea for the JPARC neutrino beam*

Due to relatively short baseline length of 295 km, the matter effect is small, and therefore the mass hierarchy may not be determined in this experiment as understood from figure 11 (left).

The T2K experiment will use an off-axis beam. It is noticed that, with the present T2K beam-line configuration, the 2.5° (or more generally any angle between 2° and 3°) off-axis beam in Kamioka (which is 295 km away from the target) and Korea (which is more than 1000 km away from the target) is simultaneously available.

It is known that the size of CP-phase effects become larger by approximately a factor of 3 in the second oscillation maximum compared with the first oscillation maximum. Figure 11 represents the energy dependence of the oscillation probabilities when they are seen by detectors in Kamioka and in Korea. In contrast to the quiet behavior in Kamioka, the ellipses are larger in size and strongly dependent

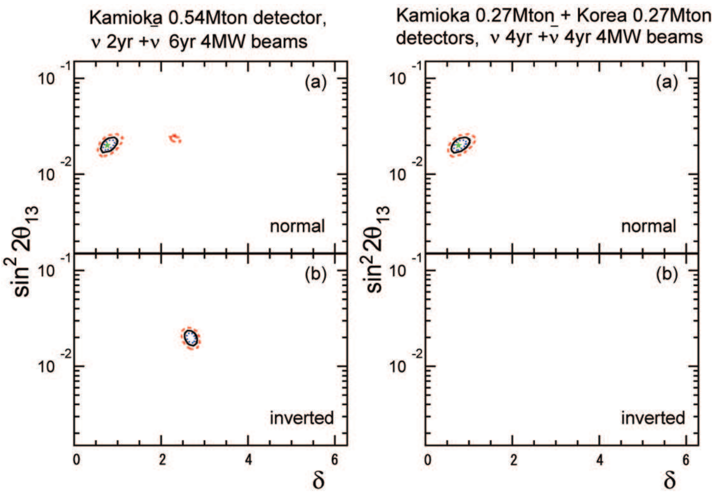

Figure 12. The expected allowed regions of neutrino oscillation parameters at 68, 90 and 99% CL for a 0.54 Mton detector at Kamioka (left) and for 0.27 Mton detectors at Kamioka and Korea (right). The total period of the experiment is eight years. The true parameters are assumed to be $\delta = (\pi/4)$, $\sin^2 2\theta_{13} = 0.02$ and the normal mass hierarchy.

on the neutrino energy in Korea. The strong energy dependence of the appearance oscillation probabilities in Korea, which are different for normal and inverted hierarchies, is the key to the high sensitivity of the two-detector complex. There exists great merit in using two identical detectors together with the neutrino beam of identical spectrum shape (in the absence of oscillations) which demonstrates the clean determination of the CP-violation and the mass hierarchy.

In order to understand the advantage of the two detector systems at 295 km (Kamioka) and 1050 km (Korea), a detailed χ^2 analysis was carried out taking into account various detector effects, such as background contamination, detection efficiency, and their systematic errors [29]. Figure 12 shows, as an example, the allowed regions in the (δ, $\sin^2 2\theta_{13}$) plane for the normal and inverted mass hierarchies. In this figure, the true parameters are assumed to be $\delta = (\pi/4)$, $\sin^2 2\theta_{13} = 0.02$ and the normal mass hierarchy. The left and right panels are for a 0.54 Mton detector at Kamioka and for 0.27 Mton detectors at Kamioka and Korea, respectively. As expected, if the experiment has only one detector in Kamioka, the mass hierarchy is typically unresolved, and therefore (at least) two solutions, one with the right mass hierarchy and the other with the wrong hierarchy, exist. On the other hand, wrong mass hierarchy solution is excluded in many cases, if the experiment has detectors in both Kamioka and Korea.

Five different mass ratios of Kamioka to Korean detectors were examined, keeping the total mass constant. Figure 13 shows the contours of sensitivity to the mass hierarchy at two and three standard deviations on δ–$\sin^2 2\theta_{13}$ plane for these five detector configurations. Here, the two and three standard deviations are defined to be $\chi^2_{\rm min}$(wrong hierarchy) $-\chi^2_{\rm min}$(true hierarchy) $>$ four and nine, respectively. As expected, better sensitivities are obtained for detector configurations with detectors

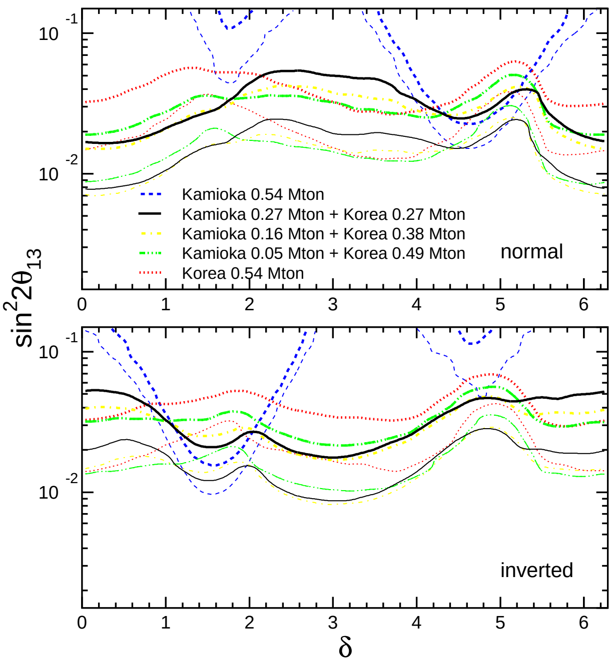

Figure 13. Two (thin lines) and three (thick lines) standard deviation sensitivities to the mass hierarchy for various volume ratios of the detectors. The total mass of the detectors is always assumed to be 0.54 Mton. Four years running with neutrino beam and another four years with anti-neutrino beam are assumed. The upper and the lower panels correspond to the cases for the normal and the inverted mass hierarchies, respectively.

both in Kamioka and in Korea. It was found that the sensitivity on the mass hierarchy does not depend strongly on the mass ratio of the two detectors. Similarly, the sensitivity to the leptonic CP-violation was studied.

Also searched for was the best option for the neutrino and anti-neutrino running time assuming the whole experimental period of eight years. Overall, two 0.27 Mton detectors in Kamioka and Korea, and four years of neutrino and four years of anti-neutrino beams are selected as the optimal choice.

Figure 14 presents the sensitivity regions for the mass hierarchy and CP-violation at two and three standard deviations in space spanned by $\sin^2 2\theta_{13}$ and the fraction of δ. In the Kamioka–Korea detector system, the mass hierarchy can be resolved if $\sin^2 2\theta_{13}$ is larger than 0.055(0.03) at the 3(2) standard deviation level for any δ values. Also, the sensitivity of the Kamioka–Korea detector system to the CP-violation is better than that of the Kamioka-only case for large $\sin^2 2\theta_{13}$. This can be easily understood by the fact that, in the case of the Kamioka detector only, the mass hierarchy is not resolved. There is (at least) one allowed δ region in each mass hierarchy. In order to demonstrate the CP-violation, one needs to demonstrate that $\sin\delta$ is not zero in each mass hierarchy case. Therefore, the Kamioka-only system has the worse sensitivity to the CP-violation.

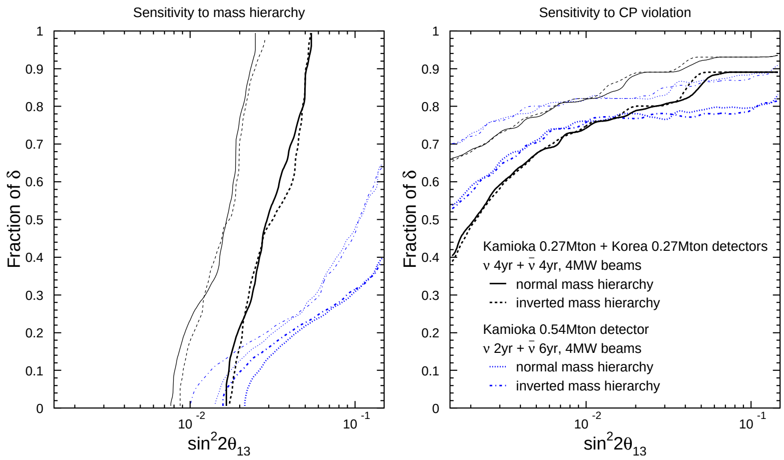

Figure 14. Two (thin line) and three (thick lines) standard deviation sensitivities to mass hierarchy (left panel) and CP-violation (right panel). Solid and dashed black lines show the cases of two identical detectors with fiducial mass of 0.27 Mton in Kamioka and in Korea with four years of neutrino and four years of anti-neutrino beam running. Dotted and dash–dotted blue lines show the cases for a single detector with fiducial mass of 0.54 Mton in Kamioka with two years of neutrino and six years of anti-neutrino beams. Solid (dotted) and dashed (dash–dotted) lines show the cases for positive and negative mass hierarchies, respectively.

6. Summary

During the last decade, there were breakthroughs in neutrino physics. The studies of the solar, reactor, atmospheric and accelerator neutrinos led to a fairly detailed understanding of neutrino oscillations. $|\Delta m^2_{23}|$, θ_{23}, Δm^2_{12}, and θ_{12} are already measured accurately. However, various parameters such as the sign of Δm^2_{23}, θ_{13}, the CP phase δ are unknown. T2K has the potential to study the neutrino properties related to these parameters. θ_{13} will be searched for in the first phase of T2K. If θ_{13} is found to be non-zero, T2K hopes to proceed to the next phase. In this phase, much larger detector(s) will be required to carry out the expected neutrino oscillation studies. We conclude that T2K has high sensitivities to various measurements if $\sin^2 2\theta_{13}$ is larger than 0.01. We expect that neutrino oscillation experiments will continue to give us new and crucial information on the understanding of the particle physics.

Acknowledgements

This work was partly supported by the Grant-in-Aid for Scientific Research by JSPS.

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