Present status and future prospects of the atmospheric neutrino experiments

Takaaki Kajita

Institute for Cosmic Ray Research, Univ. of Tokyo
Kashiwa-no-ha 5-1-5, Kashiwa, Chiba 277-8582, Japan

Abstract. During the last several years, the understanding of the neutrino masses and mixings has been improved significantly. In this article, we discuss neutrino oscillation studies in atmospheric neutrino experiments. Prospects of future atmospheric neutrino experiments are also discussed.

1. Introduction

Study of neutrino masses and mixings is one of a few ways to explore physics beyond the standard model of particle physics. In the three-flavor oscillation framework, neutrino oscillations are parametrized by three mixing angles (θ_{12}, θ_{23}, and θ_{13}), three mass squared differences (Δm^2_{12}, Δm^2_{23}, and Δm^2_{13}; among the three Δm^2's, only two are independent) and one CP phase (δ). However, if a neutrino mass hierarchy is assumed, the three Δm^2's are approximated by two Δm^2's, and the neutrino oscillation lengths are significantly different for the two Δm^2's. One $\Delta m^2(\Delta m^2_{12})$ is related to solar neutrino experiments[1]. The other $\Delta m^2(\Delta m^2_{23})$ is related to atmospheric(, reactor and long baseline) neutrino experiments. In this article, we discuss neutrino oscillation studies by atmospheric neutrino experiments.

Cosmic ray interactions in the atmosphere produce neutrinos. Although the absolute flux is uncertain by $\pm 20\%$, there are various accurate predictions such as the zenith-angle distribution of the flux and the ν_μ/ν_e flux ratio. Neutrino oscillations are discovered by studies of the ν_μ/ν_e flux ratio and the zenith angle dependent deficit of ν_μ events[2][3]. Recently, there has been a significant improvement in the understanding of neutrino masses and mixings by detailed studies of the atmospheric neutrinos.

2. Present status of atmospheric neutrino studies

Atmospheric neutrino events detected in underground detectors can be classified as fully contained (FC) events, partially-contained (PC) events, upward stopping muon events, and upward through-going muon events. The typical neutrino energies for FC, PC, upward stopping and upward through-going muon events are of the order 1, 10, 10, and 100 GeV, respectively. Super-Kamiokande, a 50,000 ton water Cherenkov detector, has

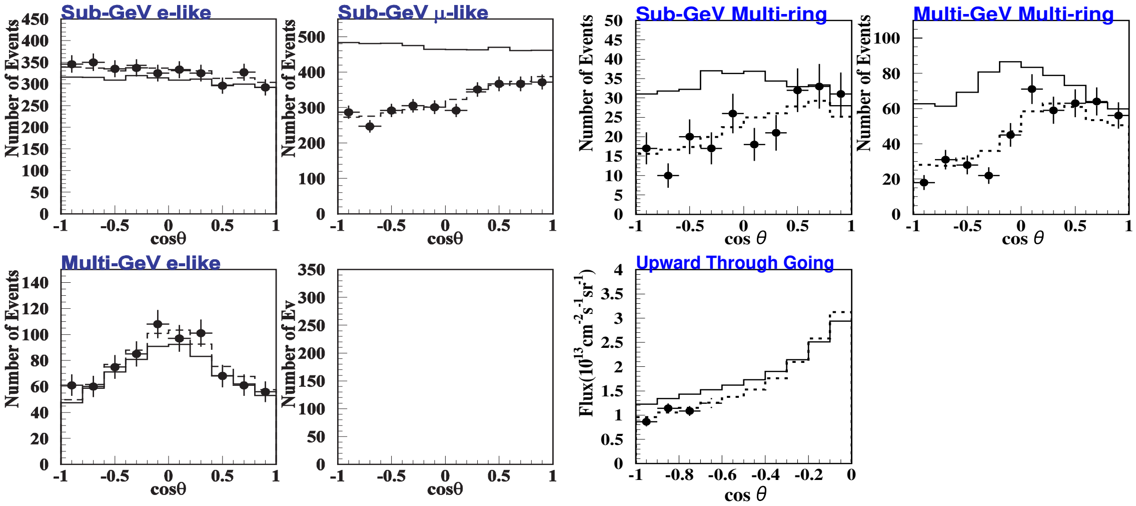

Figure 1. Zenith angle distributions observed in Super-Kamiokande based on 92 kton·yr data for various data samples. CosΘ =1(-1) means down-going (up-going). The solid histograms show the prediction without neutrino oscillations. The dashed histograms show the prediction with $\nu_\mu \to \nu_\tau$ oscillations (Δm^2_{23} =2.5$\times 10^{-3}$ eV^2, $\sin^2 2\theta_{23}$ =1.0). In the oscillation prediction, various uncertainty parameters such as the absolute normalization were adjusted to give the best fit to the data.

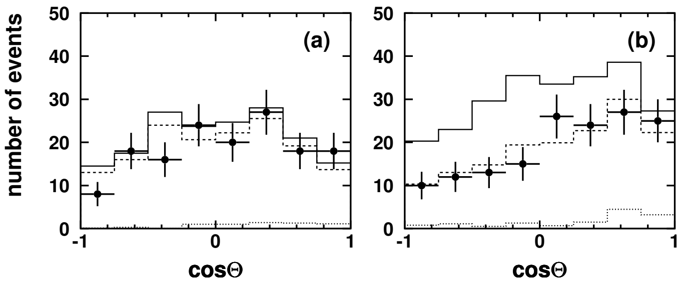

Figure 2. Zenith angle distributions observed in Soudan-2 based on 5.9 kton·yr data for the (a) CC ν_e and (b) CC ν_μ samples. The solid, dashed and dotted histograms show the Monte Carlo prediction without neutrino oscillations, with neutrino oscillations and the estimated background events, respectively.

observed all these types of events. Soudan-2, a 1kton fine-grained iron calorimeter, has observed FC events. However, upward-going muons have not been identified due to the lack of the fast timing and the resulting ambiguity between upward- and downward-going muons. MACRO, a liquid scintillator detector combined with tracking devices, has observed upward going muons and PC events.

The zenith angle distributions for e-like and μ-like events observed in Super-Kamiokande (92 kton·yr) are shown in Fig.1[4]. The μ-like data have exhibited a strong deficit of upward-going events, while no significant deficit has been observed in the e-like data. Figure 2 shows the zenith angle distributions observed in Soudan-2 (5.9 kton·yr)[5]. Although the statistics of the Soudan-2 data are limited, the observed zenith angle-dependent deficit of μ-like events is consistent with the Super-Kamiokande data. Figure 3 shows the zenith angle distributions for three data samples observed in MACRO[6]. The MACRO data are also consistent with neutrino oscillations.

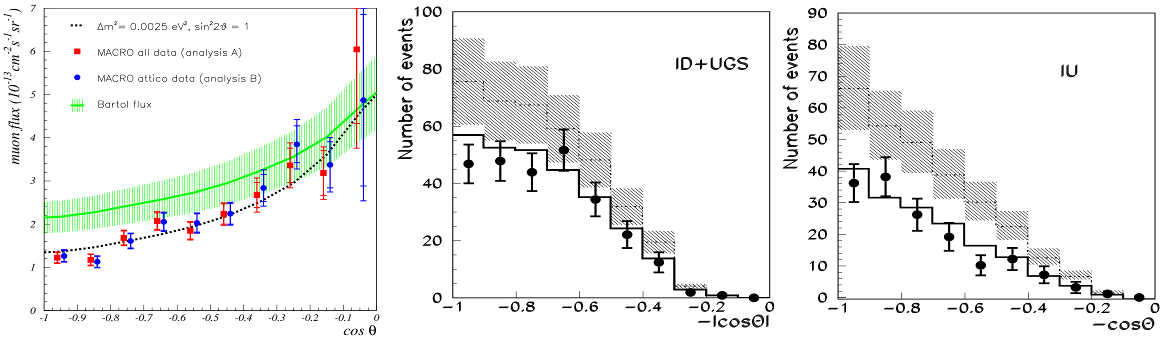

Figure 3. Zenith angle distributions for the upward through-going muon flux (left), upward stopping muons plus downward PC events (middle) and upward PC events (right) observed in MACRO. The lines with the shaded regions show the expectation for null oscillations with the absolute normalization uncertainty in the expectation. The dashed line (left) and the solid lines (middle and right) show the expected flux for $\nu_\mu \to \nu_\tau$ oscillations with ($\sin^2 2\theta_{23}$ =1.0, Δm^2_{23} =2.5×10^{-3} eV^2).

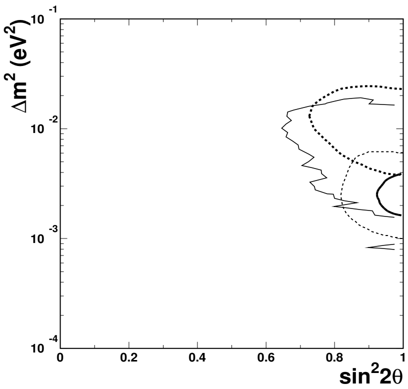

Figure 4. 90% C.L. allowed regions for the $\nu_\mu \to \nu_\tau$ oscillation parameters from Super-Kamiokande (thick line), Kamiokande (thick dotted line), Soudan-2 (thin line) and MACRO(thin dotted line).

2.1. Two and three flavor neutrino oscillation analyses

The allowed parameter regions for $\nu_\mu \to \nu_\tau$ oscillations are shown in Fig. 4. The best-fit parameter point for the Super-Kamiokande[2][4] data has been found at ($\sin^2 2\theta_{23}$, Δm^2_{23}) = (1.00, 2.5×10^{-3}eV^2). The χ^2 value of the fit for this oscillation parameter set is 163.2/170 d.o.f., thus the data are explained well by the $\nu_\mu \to \nu_\tau$ oscillation assumption. The 90% C.L. allowed parameter region is: $\sin^2 2\theta_{23} \geq 0.92$ and $1.6\times10^{-3} \leq \Delta m^2_{23} \leq 3.9\times10^{-3}$eV^2. The allowed regions obtained by the analyses from Kamiokande[3] Soudan-2[5] and MACRO[6] are also shown in Fig.4, and are mutually consistent.

As an extension of the oscillation analysis, we discuss 3 flavor neutrino oscillations. It is assumed that Δm^2_{12} is much smaller than $\Delta m^2_{23}(\Delta m^2_{13})$ as suggested by the solar neutrino data[1], and therefore the effect of the oscillations related to Δm^2_{12} is invisible in atmospheric neutrino experiments. Under this assumption, there are only three oscillation parameters; θ_{13}, θ_{23} and $\Delta m^2 (\equiv \Delta m^2_{13} = \Delta m^2_{23})$. Only θ_{13} is the new parameter, and it represents the first and third generation neutrino mixing. The allowed

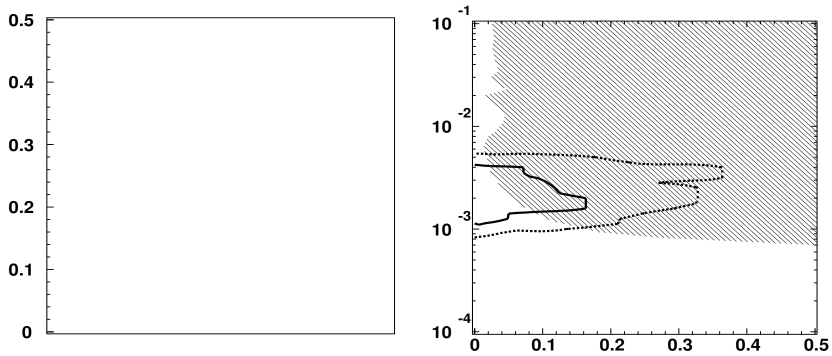

Figure 5. Allowed region on the $\sin^2\theta_{23}$ and $\sin^2\theta_{13}$ plane (left) and the $\sin^2\theta_{13}$ and Δm^2_{23} plane (right) obtained by a 3 flavor analysis of the Super-Kamiokande FC+PC data. Solid and dashed lines show the 90 and 99%C.L. allowed regions, respectively. Also shown in the right figure are the excluded regions by CHOOZ (shaded region) and Palo Verde (dashed line in the shaded region) reactor experiments.

region on the $\sin^2\theta_{13}$ and $\sin^2\theta_{23}$ plane is shown in Fig. 5. In this analysis, only FC and PC events from Super-Kamiokande are used. No evidence for non-zero $\sin^2\theta_{13}$ has been observed. The constraints on θ_{13} from reactor experiments[7][8] are still more stringent than that from atmospheric neutrino experiments.

2.2. Other interpretations

An important question to ask is whether neutrino oscillations (generated by neutrino mass and mixing) between ν_μ and ν_τ are the only possible explanation of the atmospheric neutrino data. Since the observed effect is the energy and zenith-angle dependent deficit of CC ν_μ events, there have been several proposals for alternative explanations. In this article, we discuss neutrino oscillations between ν_μ and $\nu_{sterile}$ and neutrino decays.

Pure $\nu_\mu \rightarrow \nu_{sterile}$ oscillations have been excluded using matter effect and NC events[9][6]. By using all the atmospheric neutrino data from Super-Kamiokande, neutrino oscillations between ν_μ and ν_x have been studied, where ν_x is a mixed flavor state $(\cos\xi\nu_\tau + \sin\xi\nu_{sterile})$[10]. No evidence for sterile neutrinos as a partner of the ν_μ oscillations has been observed. The upper limit on the $\nu_{sterile}$ admixture is $\sin^2\xi < 0.19$ at 90%C.L[4].

The proposed neutrino decay scenario[11] assumes that ν_μ is expressed as a combination of two mass eigenstates $(\nu_\mu = \cos\theta\nu_2 + \sin\theta\nu_3)$, $m(\nu_2)^2 - m(\nu_3)^2$ is much smaller than $10^{-4}\mathrm{eV}^2$ (hence no oscillation effect in atmospheric neutrino experiments), and one of the mass eigenstates decays to a sterile state. This scenario can successfully explain the CC atmospheric neutrino data: The best fit neutrino decay parameters that explain the Super-Kamiokande data are $(\sin^2\theta,\ m/\tau) = (0.33,\ 1.0{\times}10^{-2}\mathrm{GeV/km})$, where τ is the neutrino lifetime. The χ^2 value is 141.5/152 dof. However, this scenario predicts a deficit of NC events, because neutrinos decay into a sterile state. The observed data in Super-Kamiokande have shown no evidence for a deficit of upward-going NC events as predicted by the decay scenario. The 99%C.L. allowed region by the CC data

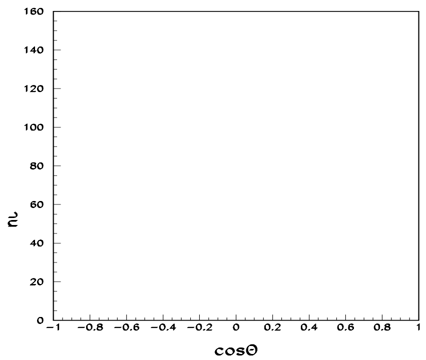

Figure 6. Preliminary zenith angle distribution for τ-like events observed in Super-Kamiokande. Circles with error bars show the data. Solid and dotted lines show the best-fit background and CC ν_τ plus background events, respectively.

have almost been excluded by the NC data at 99%C.L.[4].

2.3. Search for CC ν_τ events

If $\nu_\mu \to \nu_\tau$ is the dominant oscillation channel, about one CC ν_τ event per kiloton year exposure can be expected to occur in an atmospheric neutrino detector. The low event rate is due to the threshold effect of the τ production process which requires a ν_τ energy of at least 3.5 GeV to produce a τ lepton. These events should be upward-going but otherwise similar to energetic NC events, hence it is difficult to isolate ν_τ events in the on-going atmospheric neutrino experiments.

In Super-Kamiokande, searches for CC ν_τ events have been carried out. The candidate ν_τ events are selected by a maximum likelihood or a neural network method. Then the zenith-angle distribution is studied to estimate the number of ν_τ events statistically. Figure 6 shows the preliminary result from one analysis. The best fit numbers of ν_τ interactions is $145\pm44(\text{stat.})^{+11}_{-16}(\text{syst.})$ (preliminary). The other analysis has found $99\pm39(\text{stat.})^{+13}_{-21}(\text{syst.})$ events (preliminary). The expected number is 86. The observed numbers of ν_τ interactions are consistent with the $\nu_\mu \to \nu_\tau$ expectation. The results are not statistically compelling, however they suggest that it may be possible in the future to demonstrate the ν_τ interactions at more than 3 σ level.

3. Prospects of future atmospheric neutrino experiments

As of this writing, there have been several considerations of future detectors that can improve our knowledge on the neutrino masses and mixings through studies of atmospheric neutrinos. One type of the detectors is huge water Cherenkov detectors such as Hyper-Kamiokande[12] or UNO[13]. These detectors are assumed to have the mass of about 1 Mton. The other type of the detectors is magnetized tracking detectors. An example of the detectors is the MONOLITH[14] detector, which is a 32 kton magnetized tracking detector. The other possibility is LANNDD[15], which is a 70 kton liquid argon detector with a magnetic field inside the detector. None of the detectors has been approved yet. Therefore, we only discuss the physics potential of these atmospheric neutrino detectors.

3.1. L/E

Although the present atmospheric neutrino data give compelling evidence for neutrino oscillations, the sinusoidal L/E dependence of $P(\nu_\mu \to \nu_\mu)$ has not been observed yet. It is very important to demonstrate it experimentally. If one wants to measure the first oscillation maximum (i,e., the minimum number of μ-like events) in the L/E distribution, the typical neutrino energy is of the order of 10 GeV, since the downward and horizontal going events cannot be used due to the uncertainty in the measurement of L. To measure the muon neutrino energy in the 10 GeV range, either a very big detector to measure the muon range or a magnetized detector to measure the muon momentum is necessary. Based on detailed Monte Carlo simulations, it is claimed that a very large water Cherenkov detector[13](including Super-Kamiokande[4]) or a magnetized detector[14] can observed the first maximum oscillation point in the L/E distribution. It should be noted that, if the first maximum oscillation point is observed, the accuracy in the measurement of Δm^2 will be improved significantly.

3.2. θ_{23}, θ_{13} and the sign of Δm^2

The mixing parameters, θ_{ij}, are one of a fundamental parameters that could constrain theories beyond the standard model of the particle physics. Therefore, it is important to measure $\sin^2 2\theta_{23}$ as accurate as possible. The atmospheric neutrino flux is accurately predicted to be up-down symmetric in the multi-GeV energy range, and $(up/down)_{Data}/(up/down)_{MC} \simeq 1 - (\sin^2 2\theta_{23})/2$ to first approximation, assuming that there is no (full) oscillation effect for downward-(upward-)going neutrinos. Hence atmospheric neutrino data are useful for an accurate measurement of $\sin^2 2\theta_{23}$. The accuracy of the $\sin^2 2\theta_{23}$ measurement will be improved with (exposure time)$^{1/2}$ and will be about $\pm 2\%$ for 1 Mton·yr exposure of an water Cherenkov detector.

The other important parameter is θ_{13}. The effect of a non-zero θ_{13} could be observed as an excess of electron neutrinos in the upward-going direction through the matter resonance effect in the high energy range. For $\Delta m^2 = 3 \times 10^{-3}\mathrm{eV}^2$, the resonance could occur for neutrinos with their energies around 10 GeV. Figure 7 (left) shows a $\nu_e \leftrightarrow \nu_\mu$ oscillation probability as a function of the neutrino energy and zenith angle. A clear resonance effect is seen for upward-going neutrinos near 10 GeV. Figure 7 (right) shows the expected excess of single+multi-ring e-like events as a function of the momentum for the upward-going direction in a water Cherenkov detector. The assumed detector exposure is 0.9 Mton·yr. In this figure, $\sin^2\theta_{13} = 0.026$ (CHOOZ limit[7]) is assumed. A signal of about 4 standard deviations could be observed. However, if the true $\sin^2\theta_{13}$ is 0.005, the expected signal is less than a 2 σ effect for this exposure time. Therefore, the signal could be observed only if the true θ_{13} is close to the present limit and if the statistics of the events are improved significantly.

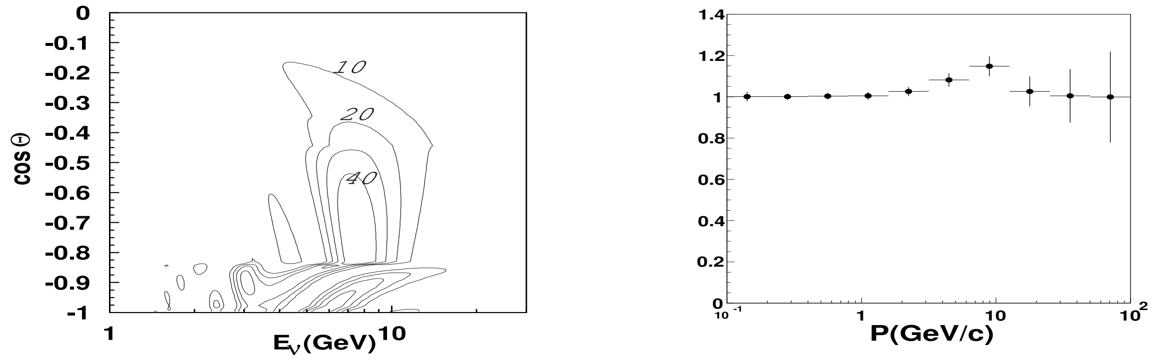

Figure 7. Left: $\nu_e \leftrightarrow \nu_\mu$ oscillation probability as a function of the neutrino energy and zenith angle. Numbers in the figure shows the probability in %. Right: Expected excess of single+multi-ring e-like events due to non-zero θ_{13} for the upward going direction ($\cos\Theta < -0.2$) as a function of reconstructed momentum. 0.9 Mton·yr exposure is assumed. In both plots, $\sin^2\theta_{23}$ =0.5 (maximal mixing), $\Delta m^2 = 3 \times 10^{-3}\mathrm{eV}^2$, and $\sin^2\theta_{13}$ =0.026 are assumed.

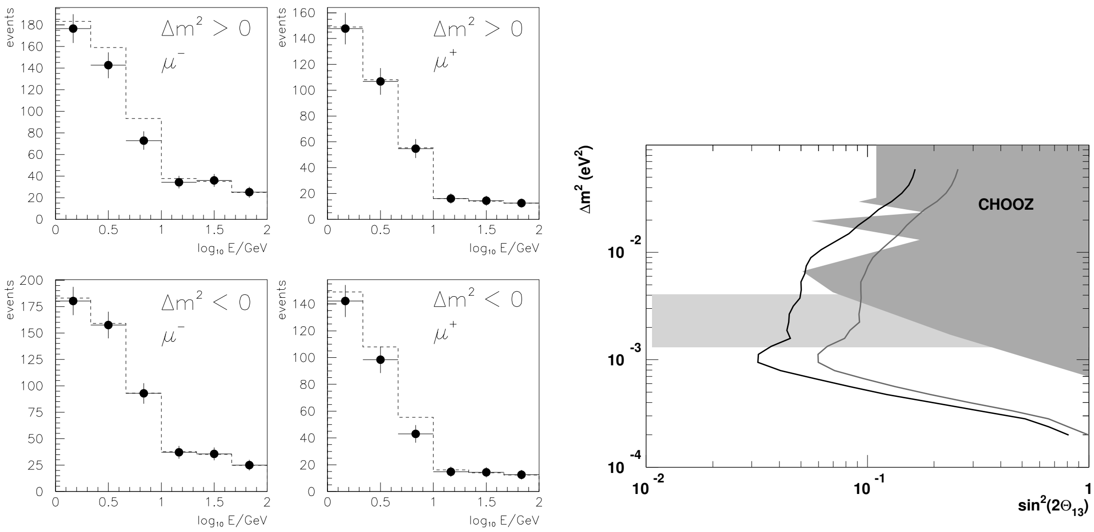

Figure 8. Left: Reconstructed neutrino energy distributions for upward going events and for a 250 kton·yr MONOLITH exposure. Dashed lines and dots show expectations for $\sin^2\theta_{13}$ =0 and 0.02, respectively. Right: Region of oscillation parameters where the sign of Δm^2 can be determined at 90%C.L.

The same effect could also be observed in the muon neutrino measurements. Figure 8 (left) shows the expected energy distributions with and without finite θ_{13}. The resonance effect only modifies the μ^- spectrum for positive Δm^2, since the resonance effect occurs for neutrinos only. This in turn suggests that the sign of Δm^2 can be measured by an atmospheric neutrino experiment that has the muon charge measurement capability. Figure 8 (right) shows the sensitivity of a magnetized atmospheric neutrino detector for the measurement of the sign of Δm^2. It is possible to measure the sign of Δm^2, if the $\sin^2 2\theta_{13}$ value is near the present limit and if the detector exposure is several hundred kton·yr.

4. Summary

The atmospheric neutrino data from various atmospheric neutrino experiments are in good agreement with $\nu_\mu \rightarrow \nu_\tau$ oscillations. The 90%C.L. allowed region of neutrino oscillation parameters from Super-Kamiokande is: $1.6 \times 10^{-3} < \Delta m^2_{23} < 3.9 \times 10^{-3}\mathrm{eV}^2$ and $\sin^2 2\theta_{23} > 0.92$. No evidence for non-zero θ_{13} has been observed. Many proposed non-standard explanations have been excluded.

Although the atmospheric neutrino data are explained by $\nu_\mu \rightarrow \nu_\tau$ oscillations, there are several open questions. These questions must be addressed in future atmospheric, reactor and long baseline neutrino oscillation experiments. Especially, it would be possible for the future atmospheric neutrino experiments to observe the first oscillation minimum in the L/E distribution, to measure the $\sin^2 2\theta_{23}$ and Δm^2_{23} values precisely, to observe a non-zero θ_{13} and to determine the sign of Δm^2_{23} (if θ_{13} is relatively large). The study of neutrino oscillations will continue to be an important and exciting field and atmospheric neutrino experiments can still contribute to this field substantially.

5. Acknowledgments

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