Frascati Physics Series Vol. XXXV (2004), pp. 53-62
HEAVY QUARKS AND LEPTONS - San Juan, Puerto Rico, June 1-5, 2004

ATMOSPHERIC NEUTRINOS: PAST, PRESENT AND FUTURE

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

ABSTRACT

Neutrino oscillations was discovered by studying atmospheric neutrinos. The present data are consistent with pure 2 flavor $\nu_\mu \rightarrow \nu_\tau$ oscillations. The allowed $\nu_\mu \rightarrow \nu_\tau$ oscillation parameter region is $\sin^2 2\theta_{23} > 0.92$ and $1.5 < \Delta m^2_{23} < 3.4 \times 10^{-3}\mathrm{eV}^2$ at 90%C.L. Recent data from an L/E analysis found that the ν_μ disappearance probability obeys the sinusoidal function as predicted by neutrino oscillations. Future atmospheric neutrino experiments are also discussed emphasizing the measurement of θ_{13} and the sign of Δm^2.

1 Introduction

Recently, neutrino oscillations have been studied extensively, since studies of neutrino masses and mixing angles are one of the few ways to explore physics beyond the standard model of particle physics.

Atmospheric neutrinos are produced by cosmic ray interactions in the atmosphere. The atmospheric $(\nu_\mu + \overline{\nu}_\mu)/(\nu_e + \overline{\nu}_e)$ flux ratio is accurately predicted to be about 2 in the GeV energy region. Also, the atmospheric neutrino flux is predicted to be up-down symmetric for the neutrinos above a few GeV where the geomagnetic field effect on the incident primary cosmic ray particles can be neglected. Neutrino oscillations can be studied by comparing these predictions and the experimental data. Atmospheric neutrinos in the 1 GeV energy range are typically observed as fully-contained (FC) events, which are events occurring inside the fiducial volume of a detector and all the visible secondary particles stop inside the detector. ν_μ interactions in the 10 GeV energy range typically generate muons that pass through a detector. These events are identified as partially-contained (PC) events. High energy (typically between 10 and 1000 GeV) ν_μ's that interact in the rock surrounding the detector are observed as upward going muons. Atmospheric neutrino experiments that observed these events have been contributing to the study of neutrino oscillations. This article describes the past, present and future studies of atmospheric neutrinos. Some results presented in this article have been updated after the conference.

2 Past

An initial, serious hint for the atmospheric neutrino oscillation was reported in 1988 when a smaller ν_μ/ν_e flux ratio than expected in the 1 GeV energy region was observed in Kamiokande [1]. This observation was confirmed by the IMB [2] and Soudan-2 [3] experiments. This result together with the size of the earth and the typical neutrino energy indicated the lower bound on Δm^2. In addition, these results indicated a large mixing angle. Subsequently, a zenith-angle dependent deficit of ν_μ events was observed [4] for neutrinos in the multi-GeV energy range. The zenith angle dependence implied an upper limit on Δm^2. However, the data statistics was not high enough to be conclusive. Also, both $\nu_\mu \to \nu_e$ and $\nu_\mu \to \nu_\tau$ were allowed. Following these early studies, in 1998, neutrino oscillation ($\nu_\mu \to \nu_\tau$) was discovered by Super-Kamiokande, which showed statistically significant zenith angle and energy dependent ν_μ deficit [5]. Consistent results have been obtained from the other recent atmosphreic neutrino experiments (see below).

3 Present

As of this writing, there are three major atmospheric neutrino experiments; Super-Kamiokande, Soudan-2 and MACRO. Two experiments have already stopped taking data. However the (near) final results have been published only recently. Thus results from these experiments are described.

Figure 1(top) shows the zenith angle distributions for various data samples from Super-Kamiokande [6]. The zenith angle and energy dependent deficit of μ-like (mostly charged current ν_μ) events is clearly seen. Consistent results have been obtained from the analysis of the contained events in Soudan-2 [7] and the upward-going muons and PC events in MACRO [8], see Fig. 1.

Since there is no evidence for the oscillations involving ν_e (see Fig. 1), $\nu_\mu \to \nu_\tau$ oscillation is assumed to fit the data. The allowed regions for the $\nu_\mu \to \nu_\tau$ oscillation parameters are estimated from these zenith angle distributions in Super-Kamiokande. In recent analyses in Soudan-2 [7] and MACRO [8], the data are plotted on the L/E axis and the oscillation analyses were carried out. (However, due to the limited event statistics and due to the resolution in L/E, the dip, which corresponds to the first maximum oscillation, in the L/E plots have not been observed in these experiments.) There are various sources of the systematic errors in the measurement. These errors are carefully evaluated and are taken into account in the fitting. The allowed regions of $\nu_\mu \to \nu_\tau$ oscillation parameters from these experiments are shown in Figure 2. The allowed regions from various experiments are consistent. The 90% C.L. allowed region from Super-Kamiokande is $1.5\times10^{-3} < \Delta m^2 < 3.4 \times 10^{-3}\text{eV}^2$ and $\sin^2 2\theta > 0.92$. Also shown is the allowed parameter region from the K2K long baseline experiment [9]. The allowed regions from atmospheric and long baseline experiments are consistent.

In addition, atmospheric neutrino data have been used to constrain various alternative models such as $\nu_\mu \to \nu_{sterile}$ oscillations [11] [12].

3.1 L/E analysis

Although Fig. 1 shows a clear zenith angle and energy dependent deficit of ν_μ events, these plots do not show any direct evidence for sinusoidal ν_μ survival probability as predicted by neutrino oscillations. Indeed, other models, such as

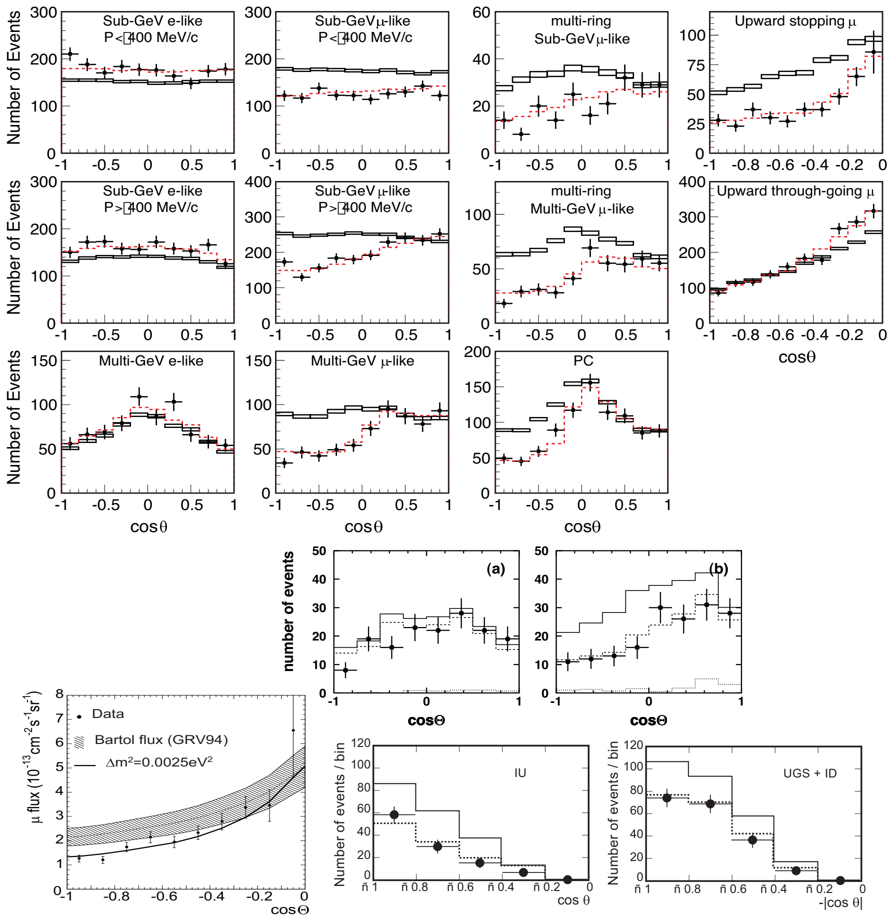

Figure 1: *Zenith angle distributions for atmospheric neutrino events observed in Super-Kamiokande (top), Soudan-2 (middle, (a)e-like, (b)μ-like) and MACRO (bottom, left: through-going muon flux, middle: upward-going PC, right: upward-going stopping muons + downward-going PC). CosΘ =1(−1) means down-going (up-going). The histograms show the prediction with and without neutrino oscillations ($\nu_\mu \to \nu_\tau$).*

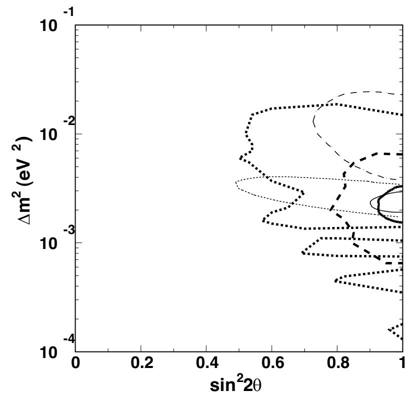

Figure 2: *90%C.L. allowed neutrino oscillation parameter regions for $\nu_\mu \to \nu_\tau$ from atmospheric neutrino experiments [10] (Kamiokande, thin dashed line) [7] (Soudan-2, thick dotted line) [8] (MACRO, thick dashed line) [6] (Super-Kamiokande, thick line). The allowed region from the L/E analysis in Super-Kamiokande is shown by the thin line. The thin dotted line shows the allowed region from K2K [9].*

the neutrino decay [14] or the decoherence [15] models, reasonably reproduce the observed atmospheric neutrino data. In order to really confirm neutrino "oscillation", it is important to demonstrate that the ν_μ survival probability obeys a sinusoidal function.

Recently Super-Kamiokande has shown evidence that the ν_μ survival probability obeys the sinusoidal function [13]. They have selected events whose L/E resolution is better than 70%. Figure 3 (left) shows data/(non-oscillated MC) for μ-like events as a function of L/E together with predictions by oscillation, decay and decoherence models. A dip was observed around L/E = 500km/GeV as predicted by Monte Carlo with neutrino oscillations. Clearly the oscillation prediction gives the best fit to the data. The χ^2 values for decay and decoherence models were 11.3 (3.4 standard deviations) and 14.5 (3.8 standard deviations) larger than that for oscillation, respectively. This is the first evidence that the neutrino survival probability obeys a sinusoidal function as predicted by neutrino oscillations. The neutrino oscillation parameters are determined by the L/E distribution. Figure 3 (right) shows the allowed parameter region from the L/E analysis. Since the dip is observed in

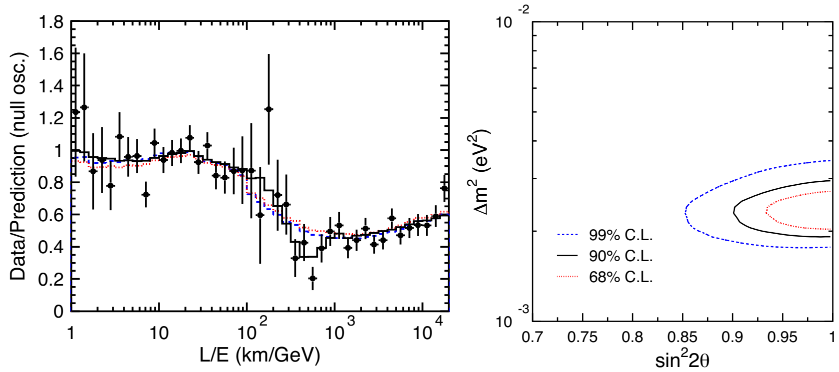

Figure 3: *Left: (Number of μ-like events)/(predicted number of μ-like events without oscillation) as a function of L/E from Super-Kamiokande. Only high L/E resolution FC+PC events were used. The solid, dashed and dotted histograms show the best-fit expectation for 2-flavor $\nu_\mu \leftrightarrow \nu_\tau$ oscillations, neutrino decay and neutrino decoherence, respectively. Right: 68, 90 and 99% allowed $\nu_\mu \to \nu_\tau$ oscillation parameter regions obtained by the L/E analysis.*

the distribution, Δm^2 value is determined accurately.

4 Future

The atmospheric neutrino experiments will continue to improve the determination of θ_{23} and Δm^2_{23} parameters with the increasing data statistics. In addition, atmospheric neutrinos should be sensitive to other oscillation parameters. The sensitivities of future atmospheric neutrino detectors in the search for non-zero θ_{13} and the determination of the sign of Δm^2_{23} are discussed.

4.1 θ_{13}

θ_{13} is a key parameter for the understanding of the neutrino mixing matrix. Therefore, various reactor and long-baseline accelerator experiments are designed to measure θ_{13}. Atmospheric neutrino experiments have sensitivities in θ_{13} as well. Assuming that the effect of Δm^2_{12} and θ_{12} can be neglected (a reasonable assumption for multi-GeV atmospheric neutrinos), for example, $\nu_\mu \to \nu_e$ oscillation probability is written as;

$$P(\nu_\mu \to \nu_e) = \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\left(\frac{1.27\Delta m^2_{23}L}{E_\nu}\right), \tag{1}$$

Since ν_e is involved in the oscillation, the matter effect [16) 17)] must be taken into account. 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 Δm^2 =2 to 3 $\times 10^{-3}$eV^2, the resonance could occur for neutrinos with their energies between 5 and 10 GeV. Figure 4 (left) shows the $\nu_e \leftrightarrow \nu_\mu$ oscillation probability as a function of the neutrino energy and zenith angle. A clear resonance effect is seen for upward-going neutrinos near 5 GeV. The present data, however, show no evidence for excess e-like events in the upward-going direction (see Fig. 1), and therefore set a limit on $\sin^2 2\theta_{13}$ as shown in Fig. 4 (right).

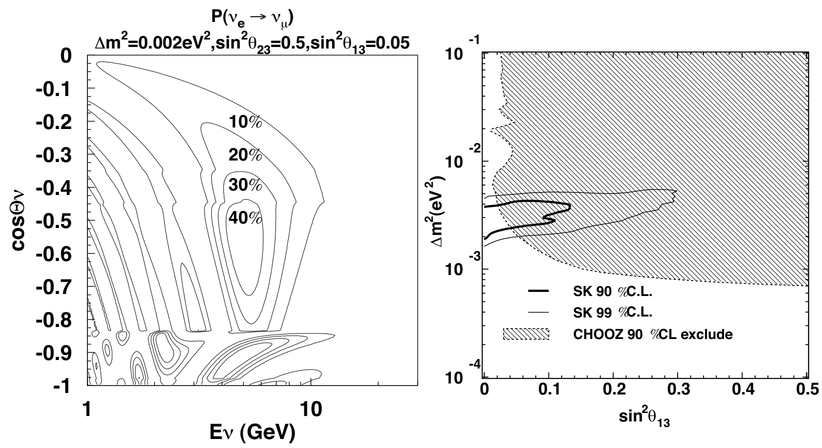

Figure 4: *Left: $\nu_e \leftrightarrow \nu_\mu$ oscillation probability for neutrinos passing through the earth as a function of the neutrino energy and zenith angle for $\Delta m^2_{23} = +2.0 \times 10^{-3} eV^2$ (positive Δm^2), $\sin^2\theta_{23} = 0.50$ and $\sin^2\theta_{13} = 0.05$. Right: 90 and 99% C.L. allowed regions on $\sin^2 2\theta_{13}$ and Δm^2_{23} for positive Δm^2_{23} from Super-Kamiokande (1489 day data). Also shown is a 90% C.L. excluded region from the CHOOZ reactor experiment* [18)].

Figure 5 shows the expected χ^2 difference between the finite and null $\sin^2\theta_{13}$ assumptions for various $\sin^2\theta_{13}$, $\sin^2\theta_{23}$ and Δm^2_{23} values in a large water Cherenkov detector [23)]. It is evident that the chance of observing finite θ_{13} increases for larger $\sin^2\theta_{23}$ [19)]. It is also found that the sensitivity does not depend strongly on Δm^2_{23}. Because of the matter effect, the sensitivity slowly changes above $\sin^2\theta_{13} = 0.01$. It seems that the improvement of the data statistics by a factor of about 5 compared with the present statistics in

Super-Kamiokande is very important to observe a non-zero θ_{13}.

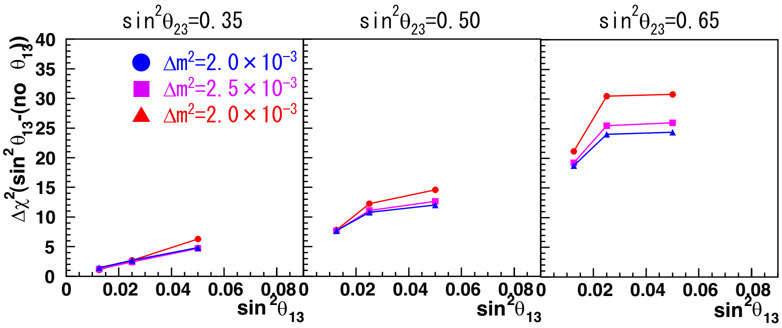

Figure 5: *Expected* χ^2 *difference between the finite and null* $\sin^2\theta_{13}$ *for* $\Delta m^2_{23}=$ *+2.0 (circle), 2.5 (square) and 3.0* $\times 10^{-3} eV^2$*(triangle) (positive* Δm^2_{23}*), and* $\sin^2\theta_{23}=$ *0.35(left), 0.5 (center) and 0.65 (right). The detector exposure is assumed to be 450 kton·yr.*

The resonance effect occurs only for neutrinos for positive Δm^2, and therefore only appears for the e^- and μ^- spectrum. This, in turn, suggests that the sign of Δm^2_{23} could be measured by atmospheric neutrino experiments that are sensitive to the charge of the leptons. Large magnetized detectors [20] [21] could be sensitive to the sign of Δm^2_{23}. It is expected that these detectors can determine the sign of Δm^2_{23} if $\sin^2 2\theta_{13}$ is larger than 0.1 (0.05) for the detector exposure of 200(400) kton·yr [20].

Super-Kamiokande and other water Cherenkov detectors are unable to distinguish ν_e and $\overline{\nu}_e$ interactions event-by-event bases. However, the cross section and the y $(= (E_\nu - E_{lepton})/E_\nu)$ dependence of the cross section are different between ν and $\overline{\nu}$, and therefore it may be possible to distinguish the positive and negative Δm^2_{23}. Since the neutrino interactions produce more high-y events (i.e., more multi-hadron events) than the anti-neutrino interactions, a larger effect of the finite θ_{13} can be seen in multi-ring e-like events for positive Δm^2_{23} than for negative Δm^2_{23}. It was concluded, based on a detailed MC study, that it is possible to measure the sign of Δm^2_{23} in water Cherenkov detectors, if the $\sin^2\theta_{13}$ and $\sin^2\theta_{23}$ values are near the present limit and $\geq$0.5, respectively, provided that the detector exposure is about 1 Mton·yr or larger [23].

The present study does not include the oscillation terms that are related to solar neutrinos (θ_{12} and Δm^2_{12}). It has been pointed out that the θ_{12} and Δm^2_{12}

terms could play unique roles to the atmospheric neutrino oscillations, such as the possible measurement of $\sin^2\theta_{23}$, (i.e., the discrimination of θ_{23} >45° and <45°) [22]. These effects should be studied seriously taking various systematic errors into account.

5 Summary

Neutrino oscillation was discovered by studies of the atmospheric ν_μ/ν_e flux ratio and the zenith angle dependence of the atmospheric neutrino flux. Atmospheric neutrinos are still playing a major role in the study of neutrino oscillations. The present data from various experiments are explained well by $\nu_\mu \rightarrow \nu_\tau$ oscillations. The recent L/E analysis from Super-Kamiokande has shown that the ν_μ disappearance probability obeys the sinusoidal function as predicted by neutrino oscillations, excluding various other explanations of the data.

If the data statistics are high enough, future atmospheric neutrino experiments could measure θ_{13} and the sign of Δm^2_{23}. It is likely that future atmospheric neutrino experiments will continue to make unique contributions to the study of neutrino oscillations.

6 Acknowledgements

This work has been supported by the Japanese Ministry of Education, Culture, Sports, Science and Technology.

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