Atmospheric and Long-Baseline Neutrinos

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Abstract. Recent results and near future prospects of atmospheric neutrino observations and accelerator-based long baseline neutrino oscillation experiments are presented.

1. Introduction

Since the discovery of atmospheric neutrino oscillations in 1998, remarkable progress has been made in neutrino physics. In particular, accelerator-based long baseline neutrino oscillation experiments play important roles not only for the confirmation of atmospheric neutrino oscillations and determination of their oscillation parameters, but also for the future measurements of $\theta_{13}$ and CP violating phase $\delta$ in the MNS matrix and neutrino mass hierarchy. This talk mainly addresses the recent results from atmospheric neutrino observations including non-oscillation physics and accelerator-based long baseline neutrino oscillation experiments. Near future prospects of atmospheric and accelerator long baseline experiments are also briefly mentioned.

2. Non-oscillation physics from atmospheric neutrino measurements

The topics for very high-energy neutrinos are covered by F. Halzen [1]. Here we review new results and future prospects for non-oscillation physics from atmospheric neutrino measurements below $O(10-100)$ TeV.

2.1. Muon charge ratio measured by the MINOS far detector

The only new result to mention here is the muon charge ratio measured with the 5.4 kt MINOS far detector (for more details, see Section 3.2) which is the first large magnetic detector located deep underground at a depth of 2070 m.w.e. At this depth, the average charge ratio is measured to be $N_{\mu^+}/N_{\mu^-} = 1.374 \pm 0.004\text{(stat)}^{+0.012}_{-0.010}\text{(sys)}$. Figure 1 shows $N_{\mu^+}/N_{\mu^-}$ as a function of $E_{\mu,0}$, where $E_{\mu,0}$ is the muon energy at the surface projected back from the muon momentum as measured underground. The MINOS measurement [2] covers $E_{\mu,0} = 1 - 7$ TeV and offers the first high-statistics data in the TeV energy range. At lower energies of 0.3 - 1 TeV, L3+C data [3] are also plotted. These data show a rise of the muon charge ratio with energy in the TeV range. In Figure 2, other muon charge ratio data are also shown together with the MINOS and L3+C results. The curve shown in Figures 1 and 2 is calculated with a simple “$\pi K$” model which assumes Gaisser and Stanev’s expression [4] for the muon intensity at the surface, as a function of muon energy and zenith angle, to be applicable independently for $\mu^-$ and $\mu^+$. According to this
qualitative model, the rise of charge ratio as a function of $E_{\mu,0}$ is consistent with an increasing contribution of kaon decays [2].

Figure 1. Plotted are the MINOS and L3+C muon charge ratio data. The curve shows the prediction of the $\pi K$ model.

Figure 2. Muon charge ratio data from 0.1 to 7 TeV. The curve shows the prediction of the $\pi K$ model.

2.2. INO
INO (India-based Neutrino Observatory) is a proposed experiment [5] with a 50 - 100 kt magnetized ICAL (Iron CALorimeter) detector. The active elements of ICAL will be resistive Plate Chambers (RPCs). The INO site recommended by the site selection committee is the one in Nilagiri mountains near Pushep at Tamilnadu, in the Southern part of India. The depth of the underground laboratory will be comparable to that of Gran Sasso (3800 m.w.e.). INO is planning a two-phase approach to scientific programs. In the first phase, INO will be a high-precision atmospheric neutrino experiment with muon charge identification capability. Naturally, it will extend the MINOS measurement of muon charge ratio at the deep underground site. However, the pair meter technique (method based on the energy dependence of the cross section of electron pair production by muons [6]) will allow the measurements of 10 - 300 TeV muons. Of course, INO will have capabilities of measuring atmospheric neutrino oscillations. Measurements of signatures of matter effects and mass hierarchy are among the physics goals aimed at in the first phase. In the second phase, it is hoped that INO would function as a detector for a neutrino factory to be constructed somewhere in the world.

3. Neutrino oscillation results and prospects
The first evidence for the neutrino oscillation was presented by the Super-Kamiokande Collaboration in 1998 [7]. The zenith-angle distributions of the $\mu$-like events (mostly muon-neutrino initiated charged-current interactions) observed in the 50,000 ton water Cherenkov detector showed clear deficit compared to the no-oscillation expectation. This striking feature was explained to be due to almost pure two-neutrino oscillation in vacuum, $\nu_\mu \leftrightarrow \nu_\tau$, with $\Delta m^2 \sim 2 - 3 \times 10^{-3}$ eV$^2$, and a nearly maximal mixing angle, $\sin^2 \theta \sim 1$.

The $\Delta m^2 \geq 2 \times 10^{-3}$ eV$^2$ region can be explored by accelerator-based long baseline experiments with typically $E \sim 1$ GeV and $L \sim$ several hundred km. With a fixed baseline distance and narrower neutrino energy spectrum, the value of $\Delta m^2$, and also with higher statistics, the mixing angle, are potentially better constrained in accelerator experiments than from atmospheric neutrino observations. The first accelerator-based long baseline neutrino oscillation experiment K2K and the subsequent MINOS experiment confirmed the atmospheric neutrino oscillation.
3.1. $\nu_\mu$ disappearance: atmospheric neutrino results

The results from Super-Kamiokande-I (SK-I for short) measurement (April 1996 - November 2001, total exposure of 92 kt·yr) were reported in [8]. After the unfortunate accident in 2001, the Super-Kamiokande detector was rebuilt within a year with about half of the original number of photomultiplier tubes. The experiment with the rebuilt detector is called SK-II. The Super-Kamiokande collaboration has released the SK-I (92 kt·yr) and SK-II (49 kt·yr) combined preliminary results last year (SK-I+II 2006). The qualitative features of the zenith-angle distributions of various categories of events (fully-contained sub-GeV and multi-GeV $e$-like/$\mu$-like, partially-contained, and upward-going muon events) look quite consistent with the SK-I results [8]. A two-neutrino oscillation analysis with the hypothesis of $\nu_\mu \leftrightarrow \nu_\tau$ using the SK-I+II 2006 zenith-angle distributions gave the best fit to the data with $\sin^2 2\theta = 1.00$ and $\Delta m^2 = 2.5 \times 10^{-3} \text{ eV}^2$. Figure 3 shows the 68%, 90%, and 99% CL allowed regions in the ($\sin^2 2\theta, \Delta m^2$) plane. At 90% CL, the allowed parameter ranges are $1.9 \times 10^{-3} \text{ eV}^2 < \Delta m^2 < 3.1 \times 10^{-3} \text{ eV}^2$ and $\sin^2 2\theta > 0.93$.

![Figure 3. Allowed region for the $\nu_\mu \leftrightarrow \nu_\tau$ oscillation parameters obtained from the zenith-angle distributions of the SK-I+II 2006 atmospheric neutrino data.](image)

Although the Super-Kamiokande atmospheric neutrino observations gave compelling evidence for neutrino flavor conversion $\nu_\mu \leftrightarrow \nu_\tau$ which is consistent with vacuum neutrino oscillations, other exotic explanations such as neutrino decay [9, 10] and quantum decoherence [11] may not be completely ruled out from the zenith-angle distributions alone. The firm evidence for neutrino oscillation is to confirm characteristic sinusoidal behavior of the conversion probability as a function of $L/E$ where $L$ (km) is the distance travelled and $E$ (GeV) is the energy of the neutrino. It should be noted that $L$ and $E$ are reconstructed from the observed quantities. By selecting events with high $L/E$ resolution from the SK-I+II 2006 data, evidence for the dip in the $L/E$ distribution was observed at the right place expected from the interpretation of the data in terms of $\nu_\mu \leftrightarrow \nu_\tau$ oscillations (see Fig. 4). This dip cannot be explained by alternative hypotheses of neutrino decay and neutrino decoherence, and they are excluded at about $5\sigma$ in comparison with the neutrino oscillation interpretation. The SK-I+II 2006 results are consistent with, and update, the SK-I L/E results [12]. Figure 5 shows 68%, 90%, and 99% CL allowed regions in the ($\sin^2 2\theta, \Delta m^2$) plane. The best fit was obtained at $\sin^2 2\theta = 1.00$ and $\Delta m^2 = 2.3 \times 10^{-3} \text{ eV}^2$. At 90% CL, the constraints obtained from the L/E analysis are $2.1 \times 10^{-3} < \Delta m^2 < 2.7 \times 10^{-3} \text{ eV}^2$ and $\sin^2 2\theta > 0.96$. These results are consistent with the SK-I+II 2006 zenith-angle analysis of fully-contained, partially-contained, and upward-going muon events (see Fig. 3).

3.2. $\nu_\mu$ disappearance: accelerator-based long baseline experiments

The K2K experiment with the baseline distance of 250 km started data-taking in June 1999 and data were intermittently taken until November 2004. The final $\nu_\mu$ disappearance results have been reported in [13]. A two-flavor neutrino oscillation analysis using the observed number of
Figure 4. L/E analysis using the SK-I+II 2006 data. The points are the ratio of the data to the Monte Carlo expectation without neutrino oscillation as a function of the reconstructed L/E. Lines are the best-fit expectations for neutrino oscillation (solid line having a dip at L/E ∼ 5 × 10^2), neutrino decay (dotted line) and neutrino decoherence (solid line with no dip).

Figure 5. Allowed oscillation parameter regions for 2-flavor νμ ↔ ντ oscillation, obtained from the SK-I+II 2006 L/E analysis.

fully contained events and the shape of the reconstructed Eν spectrum gave the best fit point in the unphysical region, (sin^22θ, Δm^2) = (1.2, 2.6 × 10^{-3} eV^2). The allowed Δm^2 region at sin^22θ = 1.0 is between 1.9 and 3.5 × 10^{-3} eV^2 at the 90% CL with the best-fit value of 2.8×10^{-3} eV^2. The probability that the observations are due to a statistical fluctuation instead of neutrino oscillation is 0.0015% or 4.3 σ.

MINOS is a long baseline neutrino oscillation experiment with near and far detectors. Neutrinos are produced by using 120 GeV protons from the Fermilab Main Injector. The far detector is a 5.4 kt (total mass) iron-scintillator tracking calorimeter with toroidal magnetic field, located underground in the Soudan mine. The baseline distance is 735 km. The near detector is also an iron-scintillator tracking calorimeter with toroidal magnetic field, with a total mass of 0.98 kt. The neutrino beam is a horn-focused wide-band beam. Its energy spectrum can be varied by moving the target position relative to the first horn and changing the horn current.

MINOS started the neutrino-beam run in 2005. Initial results were published [14] using the data taken between May 2005 and February 2006 (Run-I). MINOS also took data from June 2006 through July 2007 (Run-II). Recently, preliminary results on the analysis of νμ disappearance using the Run-I and part of the Run-II data, corresponding to a combined exposure of 2.50 ×10^20 POT (protons on target) are reported [15]. The data used in this analysis were taken with a “low-energy” option for the spectrum of the neutrino beam (the flux was maximized in the 1-3 GeV energy range). The observed number of candidate events for charged-current νμ interaction is 563. This number is compared to 738 ± 30 events expected for no neutrino oscillation. Figure 6 compares the reconstructed νμ energy spectrum at the far detector (Run-I and part of Run-II data combined) with the predicted spectrum with and without oscillations. Figure 7 shows the ratio of the NC (neutral-current) background-subtracted spectrum to the predicted
Figure 6. Reconstructed charged-current $\nu_\mu$ energy spectrum (Run-I and part of Run-II of the MINOS data combined). The spectrum calculated with the best-fit parameters and that for no oscillation are also shown. The amount of the expected neutral-current (NC) background shown by the histogram labelled NC is small.

Figure 7. The ratio of the NC-background subtracted spectrum to the predicted spectrum for no oscillation. The histogram shows the expectation with the best-fit parameters.

Figure 8. Preliminary MINOS best-fit point (star) and the 68% and 90% CL allowed regions. Also shown are the 90% CL allowed regions from the SK-I zenith [8] and L/E [12] analyses and that from K2K [13].

Figure 9. MINOS’s preliminary best-fit point (star) and 90% CL allowed regions from MINOS [15], SK-I+II 2006 zenith analysis (see Figure 3), and SK-I L/E analysis [12] are shown.

A simultaneous fit to the reconstructed $\nu_\mu$ energy spectra assuming $\nu_\mu \leftrightarrow \nu_\tau$ two-neutrino oscillation gives the best-fit oscillation parameters of $\sin^2 2\theta = 1.00 \pm 0.08$ and $\Delta m^2 = (2.3^{+0.20}_{-0.16}) \times 10^{-3}$ eV$^2$. At 90% CL, $\sin^2 2\theta > 0.84$. Figure 8 shows the 68% and 90% CL allowed regions, compared with the 90% CL allowed regions obtained from the SK-I zenith-angle dependence [8], the SK-I L/E analysis [12], and the K2K [13] results. The preliminary MINOS best fit point is shown by the star. Figure 9 compares the 90% CL allowed regions from MINOS [15], SK-I+II 2006 zenith analysis (see Figure 3), and SK-I L/E analysis [12].
3.3. $\nu_\mu$ disappearance: future prospects

At Fermilab, significant proton accelerator improvements are expected in 2008, and MINOS envisages an exposure of $6 \times 10^{20}$ POT by the end of 2008. The uncertainty in the value of $\Delta m^2$ would be reduced to about 2/3 of the preliminary MINOS result with $2.5 \times 10^{20}$ POT. T2K experiment Phase-I now under construction at J-PARC (Japan Proton Accelerator Research Complex) will aim at $5 \times 10^{21}$ POT in 5 years [16]. T2K will use Super-Kamiokande as a far detector, with a baseline distance of 295 km. The expected accuracies of the two-flavor $\nu_\mu \leftrightarrow \nu_\tau$ oscillation parameters are $\delta(\sin^22\theta) \sim 0.01$ and $\delta(\Delta m^2) < 1 \times 10^{-4}$ eV$^2$.

3.4. $\nu_\tau$ appearance

The Super-Kamiokande group searched for the appearance of $\nu_\tau$ from $\nu_\mu \rightarrow \nu_\tau$ oscillations in the SK-I atmospheric neutrino data [17]. A characteristic topology of the hadronic decay of $\tau$ (more spherical than that of backgrounds) was taken as the signature to search. After a series of cuts to reduce the backgrounds, $\tau$ signals were selected by applying the likelihood method and, independently, neural network method. Figure 10 shows the zenith-angle distribution of the selected events. The shaded area shows an excess of $\tau$-like events. Note that these events are seen in the upward-going direction. For the likelihood analysis, the hypothesis of no $\nu_\tau$ appearance is disfavored by 2.4$\sigma$. Similar result is obtained for the neural network analysis.

![Figure 10. SK-I search for $\tau$ appearance. Zenith-angle distributions of the events selected by the likelihood (top) and neural network (bottom) methods are shown. The solid histogram indicates the best-fit including $\nu_\tau$ and the dashed histogram indicates the background. The shaded area shows a fitted excess of $\tau$-like events.](image_url)

A promising method to confirm the appearance of $\nu_\tau$ from $\nu_\mu \rightarrow \nu_\tau$ oscillations is an accelerator long baseline experiment using emulsion technique to identify short-lived $\tau$ leptons event-by-event. The only experiment of this kind is OPERA [18] with a neutrino source at CERN and a detector at Gran Sasso with the baseline distance of 732 km. The detector is a combination of the “Emulsion Cloud Chamber” and magnetized spectrometer. The CNGS (CERN Neutrinos to Gran Sasso) neutrino beam with $<E_{\nu}> = 17$ GeV is produced by high-energy protons from the CERN SPS. With so-called shared SPS operation, $4.5 \times 10^{19}$ POT/yr is expected. With this beam and 1.35 kt target mass (25% reduction with respect to the proposal), a $\nu_\tau$ appearance signal of about 10 events is expected in 5 years run. In 2007, a 3 weeks of CNGS commissioning run and another 3 weeks of physics run is scheduled. The installation of emulsion target will be finally completed in 2008.
3.5. $\nu_\mu$ appearance

Measurement of the small mixing angle $\theta_{13}$ and the CP violating phase $\delta$ in the MNS matrix is among the important goals of future neutrino experiments. In the accelerator neutrino oscillation experiments with conventional neutrino beams, $\theta_{13}$ is measured using $\nu_\mu \rightarrow \nu_e$ appearance. Its probability is given by $P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta_{13} \cdot \sin^2 \theta_{23} \cdot \sin^2 (1.27 \Delta m^2_{32} L/E)$, where $|\Delta m^2_{32}| \sim \Delta m^2_{23}$ and $\theta_{23} \sim \delta$ with $\Delta m^2$ and $\delta$ being the atmospheric neutrino oscillation parameters. By examining the exact expression for the oscillation probability, however, it is understood that some of the neglected terms have rather large effects and the unknown CP-violating phase $\delta$ causes uncertainties in determining the value of $\theta_{13}$. Actually, from the measurement of $\nu_\mu \rightarrow \nu_e$ appearance, $\theta_{13}$ is given as a function of $\delta$ for a given sign of $\Delta m^2_{32}$ (neutrino mass hierarchy). Therefore, a single experiment with fixed L and E (narrow-band $\nu$ beam energy) cannot determine the value of $\theta_{13}$ though it is possible to establish non-zero $\theta_{13}$.

If $\theta_{13}$ is not much less than the CHOOZ limit [20], $\sin^2 2\theta_{13} < 0.19$, the ongoing experiments MINOS and OPERA will have a chance to establish non-zero $\theta_{13}$. T2K Phase-I [16] will have a better sensitivity, $\sin^2 2\theta_{13} < 0.008$ (for the case of $\delta = 0$ or $\pi$). An experiment proposed in US, NO$\nu$A [19], will have a similar sensitivity.

In order to determine the value of $\theta_{13}$ in the accelerator neutrino oscillation experiments, simultaneous measurement of the CP-violating phase $\delta$ is necessary. This will be achieved by measuring the appearance probabilities of $\nu_\mu \rightarrow \nu_e$ and $\nu_\mu \rightarrow \nu_\tau$. A very high intensity neutrino beam will be required to measure CP violation in this way with a conventional neutrino beam line. T2K Phase-II [16] (with beam power upgrade and a Megaton water Cherenkov detector) and NO$\nu$A [19] with upgraded beam power are known as proposals for “superbeam” experiments.

4. Conclusions

Starting with 1998, neutrino oscillation has been established. We now know $|\Delta m^2_{32}|$ and $\theta_{23}$ from atmospheric and accelerator long baseline experiments, and we want to measure $\theta_{13}$ next. Whether we can measure $\delta$ and neutrino mass hierarchy in the future experiments is crucially dependent on the unknown size of $\theta_{13}$.

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