LONG BASELINE NEUTRINO OSCILLATION EXPERIMENTS*

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Long baseline neutrino experiments have confirmed atmospheric neutrino oscillations and improved the parameter measurement. The unknown θ_{13} neutrino mixing angle and other neutrino physics will be studied by the current and next generation long baseline neutrino experiments. In this article, a review of the experimental results is presented. I will focus on the MINOS experiment which is currently running to improve the measurements of neutrino oscillations. The future prospects of long baseline neutrino experiments are also described.

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1. Introduction

The flavor transition of neutrinos has been observed by several neutrino experiments [1–7]. This phenomenon is explained by neutrino oscillations as a consequence of finite mass and a rotation of mass and flavor eigenstates of neutrinos. In the two-flavor approximation, the survival probability of neutrino with energy E_ν (GeV) after a distance of L (km) can be expressed by the following formula:

$$P(\nu_\alpha \to \nu_\alpha) = 1 - \sin^2 2\theta \sin^2 \left(\frac{1.27 \Delta m^2 L}{E_\nu} \right) . \tag{1}$$

This equation is valid in vacuum and even in matter in case of $\nu_\mu \leftrightarrow \nu_\tau$ oscillations. The observed L/E dependence of the deficit in atmospheric muon neutrinos [2] and reactor neutrinos [5] were consistent with the sinusoidal function predicted by neutrino oscillations.

Long baseline neutrino experiments were first proposed to confirm neutrino oscillations reported from atmospheric neutrino observations. Muon neutrino beam has been used in long baseline experiments as an artificial

neutrino source. The mechanism of the neutrino generation is an analogy to that of atmospheric neutrinos. A proton beam is focused on the target, and secondary hadrons are produced. Those hadrons, mostly pions, are focused by a set of magnetic horns toward the neutrino detector. Neutrino beam is a tertiary beam produced from the decays of secondary hadrons such as: $\pi^+ \rightarrow \mu^+ + \nu_\mu$.

The mixing parameters in Eq. (1) can be precisely measured in long baseline neutrino experiments from the shape of the spectrum distortion with the fixed baseline length. Systematic uncertainties on the neutrino oscillation measurement can be largely canceled by comparing the neutrino energy spectrum observed in the far detector with the non-oscillated spectrum measured in the near detector.

2. K2K

The KEK to Kamioka (K2K) experiment is the first long baseline neutrino oscillation experiment. An almost pure muon neutrino beam is created from 12 GeV proton synchrotron (KEK–PS). The typical intensity is about 5×10^{12} protons per pulse (ppp). The far detector for K2K is the SuperKamiokande (SK) water Cherenkov detector located 250 km away from the proton target. Muons and electrons are distinguishable by the ring pattern and the Cherenkov opening angle. The near detector complex consists of a 1 kton water Cherenkov detector and fine grained detectors system. Neutrino beam direction and energy spectrum are measured by the near detector system in the absence of neutrino oscillation.
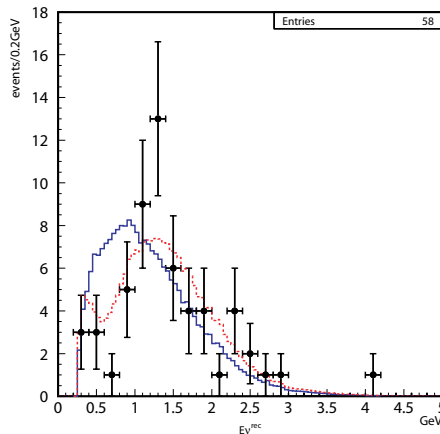

Fig. 1. Energy spectrum for the observed 58 single-ring μ-like events from the K2K experiment (points). The dashed line is the best fit spectrum with neutrino oscillations and the solid line is the expectation without oscillation. Both histograms are normalized to the number of observed events [6].

K2K have taken data from 1999 until 2004, and accumulated 9.2×10^{19} protons on target (POT) data for the physics analysis. 112 neutrino beam induced events are observed in 22.5 kton fiducial mass of the SuperKamiokande, while $158.1^{+9.2}_{-8.6}$ events are expected without oscillation [6]. Neutrino energy spectrum shape from 58 single-ring μ-like events is also used in analysis. The energy of the parent neutrino can be calculated from the observed momentum and direction of the muon, assuming charged-current (CC) quasi-elastic (QE) interactions. Observed energy spectrum for the 58 events is shown in Fig. 1. A distortion of the energy spectrum is observed as predicted by neutrino oscillation. Allowed oscillation parameter region from the measurements of the number of evens and energy spectrum shape is shown in Fig. 2, with the other experimental results.
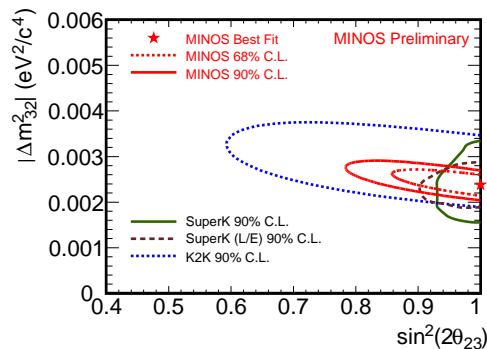

Fig. 2. Allowed Δm^2_{23} and $\sin^2 2\theta_{23}$ parameter regions from the MINOS experiment (red) [8]. Overlaid are the 90 % CL contours from the SuperKamiokande zenith angle and L/E analyses, as well as that from the K2K experiment [1, 2, 6].

3. MINOS

Main physics goal of the Main Injector Neutrino Oscillation Search (MINOS) experiment is precise measurements of Δm^2_{23} and $\sin^2 2\theta_{23}$. MINOS has been taking data from the NuMI beam since 2005, and has already accumulated 3.5×10^{20} POT by July 2007. The first results based on 1.3×10^{20} POT NuMI beam data has been published [7], and the analysis was recently updated using 2.5×10^{20} POT data [8]. The updated results are described in this section.

3.1. NuMI beam

The NuMI beam is created from a 120 GeV proton beam from the Main Injector accelerator at FNAL. Secondary pions and kaons generated in the graphite target are focused toward the MINOS detectors by a pair of magnetic horns. The relative position of the target to the horns is variable

along the longitudinal direction, and the typical neutrino energy from the focused pions can be tuned during the operation. Most of data is taken with low-energy (LE) configuration, in which the typical neutrino energy is about 3 GeV and is optimized to measure atmospheric neutrino oscillation parameters. The data from the NuMI beam with the other configurations are used to improve the hadron production model off the target. Typical intensity of the NuMI beam is 2.5×10^{13} ppp with 2.4 sec cycle time during its operation, while the beamline is designed to accept 4×10^{13} ppp.

3.2. MINOS detector

MINOS employs two detectors to reduce the systematic uncertainties associated with neutrino beam flux, interaction cross-section and detector response on the oscillation parameter measurement. The far detector is located in the Soudan Underground Laboratory 735 km away from the NuMI target. The detector is a magnetized steel-scintillator tracking calorimeter optimized to measure ν_μ CC interactions from the NuMI beam. The detector is also capable to measure ν_e CC and NC interactions. Active medium of the detector consists of 4.1 cm-wide, 1.0 cm-thick plastic scintillator strips arranged to make a plane. The detector is made of a series of the scintillator and 2.5 cm-thick steel planes. The orientations of alternating scintillator planes are rotated by $90°$ in order to reconstruct the three dimensional topology of particles. Total mass of the far detector is 5.4 kton, consists of 483 steel and scintillator planes. The near detector is based on the same technology as the far detector, and located at 1 km away from the NuMI target.

3.3. Neutrino oscillation analysis

ν_μ CC interaction candidates are selected by the event topologies based on a likelihood method. Neutrino energy is reconstructed in the MINOS detector as a combination of the muon track and hadronic shower energies. The measured neutrino energy spectrum in the near detector is extrapolated to that in the far detector using *the Beam Matrix*, which elements provide relations between the far and near detector spectra determined by the pion and kaon decay kinematics and geometry of the neutrino beamline. Monte Carlo simulation is used to correct for the energy smearing and acceptance due to the reconstruction.

563 ν_μ CC interaction candidates are observed in the far detector from an exposure of 2.5×10^{20} POT, where 738 ± 30 events are expected in the absence of neutrino oscillations. The neutrino energy spectrum for the ν_μ CC interaction candidates is shown in Fig. 3 together with the predictions. The oscillation parameters are measured by a fit to the energy spectrum assuming two-flavor $\nu_\mu \leftrightarrow \nu_\tau$ oscillations as: $\Delta m_{23}^2 = 2.38^{+0.20}_{-0.16} \times 10^{-3} \text{eV}^2$
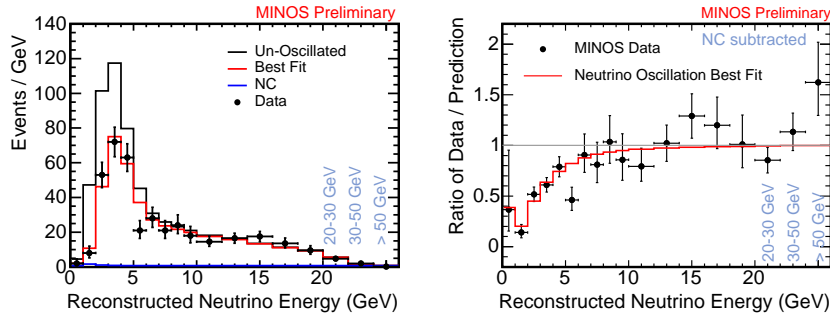
Fig. 3. Left: energy spectrum for the ν_μ CC candidates in the MINOS far detector (points), with the un-oscillated prediction (black). Also shown are the best fit prediction with neutrino oscillation (red) and the contamination of NC background (blue). Right: the ratio of the NC-subtracted energy spectrum to the un-oscillated prediction (points), with the best fit oscillation expectation (line) [8].

with errors at 68 % CL, and $\sin^2 2\theta_{23} > 0.84$ at 90 % CL. The allowed oscillation parameter regions are shown in Fig. 2.

Δm_{23}^2 and $\sin^2 2\theta_{23}$ will be measured with about 10 % accuracy after 5 years running of the NuMI running. MINOS also has potential to search for non-zero θ_{13} beyond the current limit from reactor experiment [9].

4. OPERA

Deficit of muon neutrinos has been confirmed by K2K and MINOS, while the Oscillation Project with Emulsion-tRacking Appearance (OPERA) is going to measure ν_τ appearance signal from $\nu_\mu \leftrightarrow \nu_\tau$ oscillation in the CNGS beam. The averaged energy of the CNGS beam is 17 GeV which is well above the 3.5 GeV threshold for ν_τ CC interactions. The OPERA detector is located in the Gran Sasso National Laboratory where the baseline length is 732 km. τ decay originated from ν_τ CC interaction is reconstructed in the Emulsion Cloud Chamber (ECC) brick which consists of 1 mm-thick lead and emulsion film layers. The ECC brick installation is in progress, and the detector will be completed in 2008.

12.8 ν_τ CC signal events are expected over 1.0 background events in 2.3×10^{20} POT CNGS beam data from 5 years running, assuming $\Delta m_{23}^2 = 2.4 \times 10^{-3} \mathrm{eV}^2$ and $\sin^2 2\theta_{23} = 1.0$ [10].

5. Future long baseline neutrino experiments

Atmospheric and long baseline accelerator neutrino experiments have measured $\sin^2 2\theta_{23}$ and $|\Delta m_{23}^2|$ [1,2,6,7], and solar and long baseline reactor neutrino experiments measured $\sin^2 2\theta_{12}$ and Δm_{12}^2 [3–5]. Therefore, the

next generation long baseline neutrino experiments are designed to measure the unknown parameters, θ_{13} and CP-violating phase δ, and mass hierarchy in neutrino sector. Since non-zero θ_{13} is necessary to search for δ and mass hierarchy in neutrino oscillations, the first goal must be the discovery of non-zero θ_{13}.

The next generation long baseline neutrino experiments employ an off-axis method, by which an intense narrow-band beam is available according to the pion decay kinematics. The peak of the off-axis narrow-band beam is put on the oscillation maximum to optimize the sensitivity to $\nu_\mu \leftrightarrow \nu_e$ oscillations. In addition, high energy neutrinos, and the background due to NC π^0 production, are reduced by the off-axis method. Contamination of NC and intrinsic ν_e background in the neutrino beam are measured by the near detectors.

6. T2K

The Tokai to Kamioka (T2K) experiment is a next generation long baseline neutrino oscillation experiment. T2K will use a muon neutrino beam produced by a 50 GeV PS in the J-PARC facility. The commissioning of the neutrino beamline is scheduled in 2009. The far detector for T2K is the SuperKamiokande located 295 km away at 2.5° off-axis angle. The full reconstruction of the detector has successfully finished, and it started the operation (SK-III) in 2006. The near detector complex, which includes on-axis and off-axis detectors, will be ready in 2009 for the neutrino beam. The neutrino beam direction is monitored by the on-axis detector, and the energy spectrum is measured by the off-axis detectors. Details of neutrino interactions can be also studied by the off-axis detectors. In addition, intermediate detector complex, including water Cherenkov detector, is considered after the beam commissioning to measure precise spectrum shape.

The main physics goals of T2K are the search for the non-zero θ_{13} and precise measurements of $\sin^2 2\theta_{23}$ and Δm_{23}^2. Assuming $\Delta m_{23}^2 = 2.5 \times 10^{-3}\,\text{eV}^2$, $\sin^2 2\theta_{23} = 1.0$ and $\delta = 0$, the sensitivity to $\sin^2 2\theta_{13}$ is 0.008 at 90 % CL with 5×10^{21} POT data from 5 years of the J-PARC neutrino beam running.

If $\sin^2 2\theta_{13}$ will be measured as > 0.01, it opens the door to search for CP-violation in T2K Phase-II. The plan for the Phase-II includes upgrade of J-PARC beam power from 750 kW to 4 MW, and larger detector (Hyper-Kamiokande) with 1 Mton mass. In addition, another setup with two 0.5 Mton detectors, with baseline lengths of 295 km at Kamioka, Japan and about 1050 km in Korea, is also studied for the Phase-II. This setup has additional sensitivity to neutrino mass hierarchy [12].

7. NOvA

The main physics goal of the NuMI Off-Axis ν_e Appearance (NOvA) experiment is searching for ν_e appearance signal from sub-dominant $\nu_\mu \leftrightarrow \nu_e$ oscillations [13]. NOvA also has potential to search for CP violation and resolve mass hierarchy in neutrino sector with the large matter effects induced by the 810 km long baseline. 3σ sensitivity to non-zero $\sin^2 2\theta_{13}$ is shown in Fig. 4. NOvA is scheduling to start the operation in 2011.
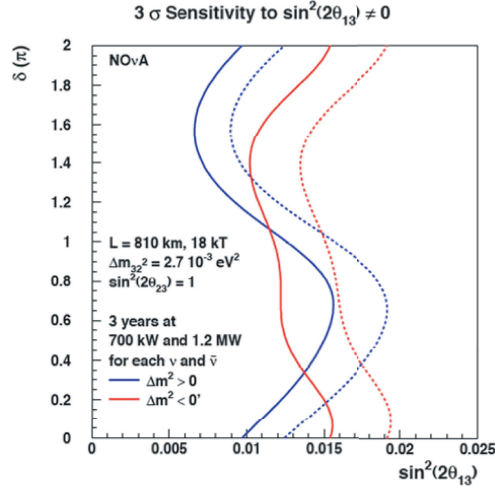

Fig. 4. Three standard deviation sensitivity to non-zero θ_{13} as a function of CP-violating phase δ with normal (blue) and inverted (red) mass hierarchy for a 6 years of NOvA running with equally split ν and $\overline{\nu_e}$ modes. The solid and dashed curves are for 1.2 MW and 700 kW beam power, respectively [14].

NOvA experiment will use the NuMI beam with its medium-energy mode. The designed NuMI beam power and intensity for the NOvA experiment are 700 kW and 6×10^{20} POT per year after the Accelerator and NuMI Upgrades (ANU). Further upgrade to 1.2 MW and 1×10^{21} POT/year, called SNuMI, is also studied. The peak of the off-axis narrow-band beam is 2 GeV on the $\nu_\mu \leftrightarrow \nu_e$ oscillation maximum.

The location of the NOvA far detector will be 810 km downstream from the NuMI target at 15 mrad off-axis angle. The active detector medium is liquid scintillator contained in 4.4 cm-wide and 6.6 cm-thick PVC extrusion cells. The plan of the total mass of the detector is 18 kton. The detector technology is designed to detect GeV electrons from ν_e CC interactions. NOvA employs the near detector 1 km downstream from the target at FNAL, where the non-oscillated energy spectrum is measured by the same technology and same off-axis angle.

8. Conclusion

Discovery of neutrino oscillations as a consequence of neutrino mixing and masses was a breakthrough to the particle physics beyond the standard model. The long baseline neutrino oscillation experiments have successfully confirmed oscillations using artificial neutrino source produced by accelerators. Unknown θ_{13} will be studied by the next generation long baseline neutrino experiments. Measurement of non-zero θ_{13} is essential to search for CP violation in neutrino sector, which is considered as a key to understand the origin of baryon-asymmetry of the Universe.

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