Status and Prospects of Neutrino Oscillation Experiments

Masaki Ishitsuka

Tokyo Institute of Technology - Department of Physics
2-12-1 Ookayama Meguro, Tokyo 152-8551 - Japan

Discovery of neutrino oscillations as a consequence of neutrino masses was a breakthrough to the particle physics beyond the Standard Model. After the discovery of neutrino oscillations, the neutrino mass squared differences and mixing angles have been measured precisely by several neutrino oscillation experiments using various sources which include solar, atmospheric and reactor neutrinos, as well as artificial neutrino beams. The status and future prospects of neutrino oscillation experiments are presented in this report.

1 Introduction

The Standard Model of particle physics has been tested for wide energy range in collider experiments, and provided successful descriptions to the experimental data. On the other hand, evidence for the phenomena beyond the Standard Model was given by neutrino experiments. In the Standard Model, neutrinos are all left-handed particles and have no mass. While the experimental data strongly support the existence of neutrino oscillations as a consequence of neutrino masses [2].

If neutrinos have finite masses and the flavor eigenstates are expressed as combinations of the mass eigenstates, flavor transitions occur in neutrinos. This phenomena is called neutrino oscillation. For simplicity, in two-flavor scheme, survival probability of ν_α with energy E_ν after traveling a distance of L is expressed as:

$$P(\nu_\alpha \to \nu_\alpha) = 1 - \sin^2 2\theta_{ij} \sin^2\left(\frac{1.27\,\Delta m^2_{ij}(\mathrm{eV}^2)\,L(\mathrm{m})}{E_\nu(\mathrm{MeV})}\right), \tag{1}$$

where θ_{ij} and Δm^2_{ij} are mixing angle between the flavor eigenstates and mass eigenstates and mass squared difference between two mass eigenstates, respectively.

In three-flavor framework, the probability is determined by three mixing angles (θ_{12}, θ_{23} and θ_{13}), three mass squared differences (Δm^2_{21}, Δm^2_{32} and Δm^2_{31}, in which only two are independent) and one CP-violation phase (δ_{CP}). If we assume hierarchy in neutrino masses, in which one mass scale is much larger or smaller than the others, three mass squared differences are approximated by two. This approximation is valid as $|\Delta m^2_{31}| \sim |\Delta m^2_{32}| \gg \Delta m^2_{21}$ according to the measurements. This allows us to understand the experimental data by simple two-flavor oscillation schemes with different oscillation length corresponding to different Δm^2 scales. One ($\Delta m^2_{21} \sim 8\times10^{-5}\mathrm{eV}^2$) is related to solar and KamLAND reactor experiments, and the other ($|\Delta m^2_{32}| \sim 3\times10^{-3}\mathrm{eV}^2$) is related to atmospheric, reactor and long-baseline experiments using artificial neutrino beams. Measurements of neutrino oscillations in these two Δm^2 scales are described in the following sections. At the end of this report, future prospects for neutrino oscillation experiments are discussed, putting focus on the measurement of the remaining unknown mixing angle, θ_{13}.

2 Measurements of Δm^2_{21} and θ_{12} by solar and reactor neutrino experiments

Observed solar neutrino flux reported by several experiments with different energy thresholds were significantly lower than the prediction from the Standard Solar Model (SSM). This was known as solar neutrino problem. The discrepancy has been resolved since then by neutrino oscillations.

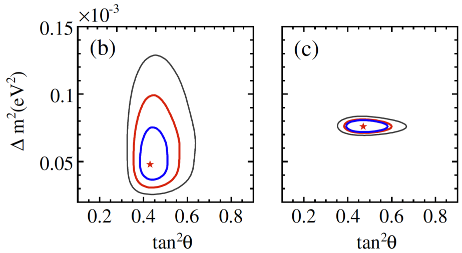

Figure 1: Allowed neutrino oscillation parameter regions from a global analysis of solar neutrino experiments (left) and solar global + KamLAND experiment (right) [3]. Three contours from the center show 68, 95 and 99.7 % CL regions, respectively.

The SNO experiment measured the solar neutrino flux using a 1 kton heavy water Cherenkov detector located at a depth of 6010 m of water equivalent. The SNO detector observes ^{8}B solar neutrinos through the charged-current (CC) interaction ($\nu_e + d \rightarrow p + p + e^-$) and neutral-current (NC) interaction ($\nu_x + d \rightarrow p + n + \nu_x$). The CC interaction is sensitive exclusively to electron neutrinos, while the NC interaction is equally sensitive to all active neutrinos. The SNO detector has been operating through three phases. In the first phase, NC signals are observed by detecting 6 MeV γ ray from neutron capture on deuterium. 2 tons of NaCl were added in the second phase to enhance the detection efficiency of NC with increased neutron capture rate by chlorine. In the third phase, Helium-3 proportional counters were installed in the detector. Neutrons from NC interactions are predominantly detected by the proportional counters. The measured total flux in the NC interaction was consistent with the SSM prediction, while the flux of electron neutrinos measured in the CC interaction was significantly lower than the prediction without neutrino oscillations [3]. This is concluded as evidence for flavor transition in solar neutrinos by $\nu_e \rightarrow \nu_{\mu,\tau}$ oscillations.

The KamLAND experiment improved the measurement of neutrino oscillation parameters. KamLAND is a long-baseline reactor neutrino experiment with 1 kton of liquid scintillator detector. The detector is surrounded by nuclear power reactor units with average distance of 180 km. The energy spectrum of $\overline{\nu_e}$ candidate events from exposure of 2881 ton·yr showed a significant distortion as predicted from neutrino oscillations [4]. Neutrino oscillation parameters, especially the mass squared difference, are precisely determined from the spectral distortion.

A global analysis of the solar neutrino experiments and KamLAND reactor neutrino experiment gives $\Delta m^2_{21} = 7.59^{+0.19}_{-0.21} \times 10^{-5}\text{eV}^2$ and $\sin^2 2\theta_{12} = 0.87 \pm 0.03$ [3]. Figure 1 shows the allowed parameters regions from the global analyses.

3 Measurements of $|\Delta m^2_{32}|$ and θ_{23} by atmospheric and long-baseline neutrino experiments

The first convincing evidence for neutrino oscillation was found in zenith angle distributions of atmospheric neutrinos by the Super-Kamiokande experiment [5]. Atmospheric neutrinos are created mainly from pion decays in atmosphere, and the zenith angle distribution of the flux is predicted to be up-down symmetric. The observed electron neutrino flux showed the up-down symmetry and was consistent with the prediction, while significant deficit was found in the muon neutrino flux for the upward direction, in which neutrinos travel longer distance through the earth. On the other hand, the observed zenith angle distributions were consistent with the prediction from $\nu_\mu \to \nu_\tau$ oscillations.

The atmospheric neutrino oscillations were confirmed by the K2K and MINOS long-baseline neutrino oscillation experiments using accelerator-based neutrino beams. In long-baseline experiments, neutrino travel distance (L in Equation 1) is fixed. Therefore, Δm^2 parameter is determined with high precision from the distortion of energy spectrum. The muon neutrino beam is created from proton beam by accelerator based on the same mechanism as atmospheric neutrinos.

The main aim of the MINOS experiment is a precise measurement of atmospheric neutrino oscillation parameters with high statistics data. A high intensity muon neutrino beam is created in the Fermilab NuMI facility from 120 GeV proton beam. MINOS employs two detector method, by which the far detector is put at a distance of 735 km where neutrino oscillation is expected and the near detector is located at 1 km downstream from the proton beam target where the effect of neutrino oscillation is negligible. By comparing the measurements from two detectors, systematic errors associated with the neutrino flux, cross-section and detector responses are canceled and precise measurement of neutrino oscillation parameters is possible. Based on two years exposure of MINOS detectors to the muon neutrino beam, MINOS reported the data was consistent with $\nu_\mu \to \nu_\tau$ oscillations with $|\Delta m^2_{32}| = (2.43 \pm 0.13) \times 10^{-3}\mathrm{eV}^2$ (68 % confidence level) and $\sin^2 2\theta_{23} > 0.90$ (90 % confidence level) [6], which especially improved the measurement of mass squared difference. Figure 2 shows the allowed parameters regions obtained by MINOS, together with those given by Super-Kamiokande and K2K.

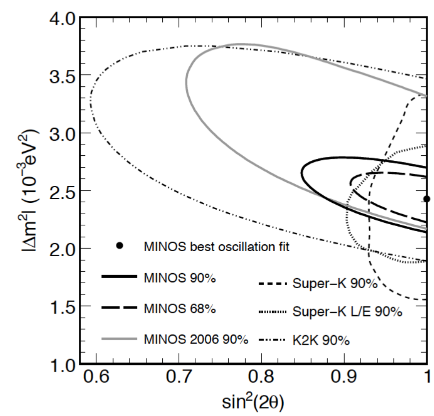

Figure 2: Allowed neutrino oscillation parameter regions from MINOS [6]. Overlaid contours are from Super-Kamiokande atmospheric neutrino observations [7, 8] and K2K long-baseline experiment [9].

4 Test of another oscillation mode at $\Delta m^2 \sim 1\,\mathrm{eV}^2$ scale

As summarized in the previous sections, oscillation lengths for the solar and atmospheric neutrino oscillations are characterized by $\Delta m^2_{21} \sim 8 \times 10^{-5}\,\mathrm{eV}^2$ and $|\Delta m^2_{32}| \sim 3 \times 10^{-3}\,\mathrm{eV}^2$, respectively. Each oscillation mode has been confirmed using independent neutrino sources. Therefore, another oscillation mode at different Δm^2 scale, if exists, requires the existence of the fourth neutrino, which may be sterile neutrinos according to the constraints of three active neutrino families.

The MiniBooNE experiment is searching for such oscillation at $\Delta m^2 \sim 1\,\mathrm{eV}^2$, where

LSND found signal from $\overline{\nu_\mu} \to \overline{\nu_e}$ oscillations. The peak of the muon neutrino beam is at 700 MeV with the baseline of 541 m, being the L/E_ν around LSND oscillation maximum.

As a result of the analysis, no ν_e appearance signal from $\nu_\mu \to \nu_e$ oscillation was found in ν_μ beam, and large fraction of parameter region from LSND was excluded [11]. The data taken in $\overline{\nu_\mu}$ beam was also consistent with no $\overline{\nu_\mu} \to \overline{\nu_e}$ oscillation, although it was not conclusive [12].

5 Prospects of future neutrino oscillation experiments

Targets of future neutrino oscillation experiments include measurements of the remaining neutrino mixing angle (θ_{13}), CP-violation phase (δ_{CP}) and mass ordering in neutrino sector, as well as precise measurements of the other oscillation parameters. Among those, measurement of θ_{13} is essential to search for δ_{CP} in future experiments since the parameter is observed as a combination with θ_{13}.

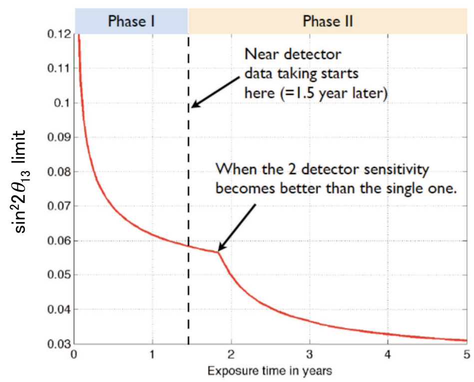

Figure 3: Projected sensitivity of Double Chooz experiment to the measurement of θ_{13}.

The current best knowledge of θ_{13} is given by the CHOOZ reactor neutrino experiment as $\sin^2 2\theta_{13} < 0.15$ for $|\Delta m^2_{32}| = 2.5 \times 10^{-3}\text{eV}^2$ [13]. The K2K and MINOS long-baseline experiments carried out ν_e appearance search in sub-dominant $\nu_\mu \to \nu_e$ oscillations, and no significant excess of ν_e events consistent with non-zero θ_{13} was found. The next generation neutrino oscillation experiments are designed to be able to improve the measurement.

Two different approaches are taken in the design of such experiments targeting measurement of θ_{13}. One uses reactor neutrinos to study $\overline{\nu_e}$ disappearance channel, and the other is long-baseline experiment searches for ν_e appearance signal from sub-dominant $\nu_\mu \to \nu_e$ oscillations in high intensity ν_μ beam.

In reactor neutrino experiments, Equation 1 is a good approximation for L less than a few km and direct measurement of θ_{13} is possible in this channel. Among several experiments proposed, the Double Chooz experiment [14] is now (as of July 2009) constructing the far detector at 1 km away from the reactor cores where $\overline{\nu_e}$ disappearance is expected from neutrino oscillations if θ_{13} is not zero. Figure 3 shows the projected sensitivity of Double Chooz to θ_{13}. Double Chooz will use two identical detectors with different baselines. After the operation with the far detector started, the near detector will be constructed at short distance from the neutrino sources where effect of neutrino oscillation is negligible. Systematic errors associated with the uncertainty in neutrino flux, number of target protons and detection efficiencies are largely canceled by comparing the measurements from two identical detectors. Double Chooz can search for the θ_{13} well beyond the limit set by CHOOZ.

In accelerator-based long-baseline experiments, the $\nu_\mu \to \nu_e$ oscillation probability is determined by combinations of θ_{13}, δ_{CP}, mass ordering and θ_{23}. The matter effects also must be taken into account. The T2K experiment will use narrow band ν_μ beam by off-axis method, by which NC backgrounds are reduced, with Super-Kamiokande as the far detector. The T2K neutrino beam-line started operation in April 2009. The projected sensitivity to $\sin^2 2\theta_{13}$ reaches by an order of magnitude beyond the current limit [15].

If θ_{13} will be measured in a certain range ($\sin^2 2\theta_{13} > 0.01$), it opens the door to search for δ_{CP} in T2K Phase-II. The plan for the Phase-II includes upgrade of beam power as well as larger detector with 1 Mton mass. 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 [16].

In addition, possibility of resolving δ_{CP} by a combination of measurements from reactor and accelerator-based long-baseline experiments is also pointed out in [17].

6 Conclusion

Discovery of neutrino oscillations as a consequence of neutrino mixing and masses was a breakthrough to the particle physics beyond the Standard Model. Several experiments reported the data consistent with three-flavor oscillation framework using various neutrino sources. The measurements of oscillation parameters were dramatically improved in the last decade. Unknown θ_{13} parameter is being studied by the current and future neutrino experiments, which include reactor and accelerator-based long-baseline experiments. Measurement of non-zero θ_{13} is essential to search for CP-violation in neutrino sector, which may hold a key to understand the origin of baryon-asymmetry of the Universe.

Acknowledgements

The author acknowledges the financial support from the Global Center of Excellence Program by MEXT, Japan through the Nanoscience and Quantum Physics Project of the Tokyo Institute of Technology.

References

[1] Slides:
`http://indico.cern.ch/contributionDisplay.py?contribId=36&sessionId=2&confId=53294`

[2] W.-M. Yao *et al.*, J. Phys. **G33**, 1 (2006).

[3] B. Aharmim *et al.*, Phys. Rev. Lett. **101**, 111301 (2008).

[4] S. Abe *et al.*, Phys. Rev. Lett. **100**, 221803 (2008).

[5] Y. Fukuda *et al.*, Phys. Rev. Lett. **81**, 1562-1567 (1998).

[6] P. Adamson *et al.*, Phys. Rev. Lett. **101**, 131802 (2008).

[7] Y. Ashie *et al.*, Phys. Rev. Lett. **93**, 101801 (2004).

[8] Y. Ashie *et al.*, Phys. Rev. **D71**, 112005 (2005).

[9] M. H. Ahn *et al.*, Phys. Rev. **D74**, 072003 (2006).

[10] Y. Fukuda *et al.*, Phys. Rev. Lett. **81**, 1562-1567 (1998).

[11] A. A. Aguilar-Arevalo *et al.*, Phys. Rev. Lett. **98**, 231801 (2007).

[12] A. A. Aguilar-Arevalo *et al.*, arXiv:0904.1958[hep-ex] (2007).

[13] M. Apollonio *et al.*, Eur. Phys. J. **C27**, 331-374 (2003).

[14] F. Ardellier *et al.*, hep-ex/060625 (2006).

[15] I. Kato for the T2K collaboration, J. Phys. Conf. Ser. **136**, 022018 (2008).

[16] M. Ishitsuka, T. Kajita, H. Minakata and H. Nunokawa, Phys. Rev. **D72**, 033003 (2005).

[17] H. Minakata *et al.*, Phys. Rev. **D68**, 033017 (2003).