Reach of Future Accelerator and Reactor Neutrino Efforts

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Numbers of accelerator and reactor neutrino oscillation experiments aiming to search finite value of $\theta_{13}$ are starting within a few years. T2K experiment is a next generation long baseline neutrino experiment starts on 2009, in Japan. A main goal of the T2K experiment is to discover a finite $\theta_{13}$ by observing $\nu_e$ appearance. Determining $\theta_{13}$ leads a next search of CP violation in the lepton sector. Status of T2K experiment and prospects for CP measurement are reported in the report.

1. Introduction

Neutrino mass and mixing matrix of the lepton sector can be explored only by neutrino oscillations. Experimental results of the neutrino oscillations are indicating that neutrino have finite mass and mixing matrix of the lepton sector is completely different from quark sector.

Atmospheric and long baseline accelerator neutrino experiments already measured $\sin^2 2\theta_{23}$ and $|\Delta m^2_{23}|$ [1]. Solar and long baseline reactor neutrino experiments have measured $\sin^2 \theta_{12}$ [2]. However, as for the third mixing angle $\theta_{13}$, only an upper limit has been determined [3]. Finite value of $\theta_{13}$ should be measured as soon as possible.

Numbers of next generation neutrino experiments using high intensity accelerator or reactor are starting within a few years. These experiments are aiming to discover the last unknown mixing angle $\theta_{13}$ by appearance ($\nu_\mu \rightarrow \nu_e$) or disappearance ($\nu_e \rightarrow \nu_\mu, \nu_\tau$) oscillation channel.

If finite $\theta_{13}$ is detected, size of the mixing could determine direction of future experiments to search leptonic CP violation term.

2. T2K experiment

T2K experiment is a 295km long baseline neutrino oscillation experiment based on accelerator in Japan. Muon neutrinos are produced by protons from 50 GeV synchrotron in J-PARC striking on a 90cm long graphite target. A large water Cherenkov detector Super-Kamiokande is used as a far detector. The main physics goals of the experiment are precise measurement of oscillation parameters, $\Delta m^2_{23}$ and $\sin^2 (2\theta_{23})$, in $\nu_\mu$ disappearance channel and discovery of finite $\theta_{13}$ by observing $\nu_e$ appearance.

2.1. Intense Narrow-band Neutrino Beam

Neutrino beam is produced by $\pi^+ \rightarrow \mu^+ \nu_\mu$ decay from the proton interaction in graphite target. Neutrino beam energy can be selected by putting detector intentionally off-axis of parent $\pi^+$ direction. We set the off-axis angle to $2.5^\circ$ in order to tune beam energy to be 0.6~0.7~GeV which corresponds that we can measure oscillation maximum at 295km baseline when $\Delta m^2_{23} = (2.2 \sim 2.6) \times 10^{-3}eV^2$.

This off-axis method gives intense narrow-band neutrino beam which about 1,600 charged current interactions per year are expected in Super-Kamiokande. It is two times larger intensity at the energy $\sim 0.7$~GeV than the case of “on-axis” wide band beam. The off-axis beam has smaller high energy tail, and it reduces background contamination for the energy reconstruction as described below.

![Figure 1: Off-axis angle dependence of mean neutrino energy.](image-url)

2.2. Near Detectors

Properties of neutrino beam “before” oscillation and its interaction are measured by near detectors. Near detectors consists of muon monitor placed at 110m downstream of proton target, and, on-axis and off-axis neutrino detectors placed at 280m downstream of proton target.

The muon monitor measures direction and intensity of neutrino beam at each spill by monitoring pion decay muons at just downstream of decay pipe. The on-axis detector monitors beam intensity, direction and profile of the neutrino beam. The detector consists of 16 modules of iron and scintillator tracker blocks. About 10k neutrino interactions per day is expected and measures beam direction within 1mrad accuracy.
The off-axis detectors are placed at $2.0 - 2.5^\circ$ off-axis region from the beam center to measure neutrino beam goes to Super-Kamiokande. Detectors are surrounded by a large dipole magnet (re-use of UA1 magnet) which produces 0.2 T uniform magnetic field. Upstream half consists of scintillator / Pb layers and 40% of $H_2O$ target which dedicated to measure NC $\pi^0$ components. Downstream half consists of two fine grained detectors that one is carbon target, another is $H_2O$ target, three TPC, tracker calorimeter and side muon range detector. Iron of dipole magnet is also used as a part of muon range detector. The detector measures off-axis beam flux, energy spectrum, CC $1\pi^+$, NC $1\pi^0$ backgrounds, and used for neutrino cross-section studies.

2.4. Physics Prospect

2.4.1. $\theta_{13}$: $\nu_e$ Appearance Measurement

We measure $\nu_e$ appearance signal in $\nu_\mu$ beam by detecting Cerenkov ring of single electron from $\nu_e$ CCQE interaction in Super-Kamiokande.

Major backgrounds in the search are intrinsic $\nu_e$ in the beam and mis-identification to single electron of single $\pi^0$ production in NC interactions. The $\nu_e$ component in the beam is 0.4% at the peak of beam energy. The NC $\pi^0$ is mis-identified when one of two photons from $\pi^0$ decay is mis-reconstructed or two Cerenkov rings are overlapped.

In addition to the selection criteria for the single electron used in the Super-Kamiokande atmospheric neutrino analysis, we apply specific $e/\pi^0$ separation cuts in order to further reduce NC $\pi^0$ background events. Then events which reconstructed neutrino energy between 0.35 GeV and 0.85 GeV are selected. Expected signals and backgrounds are shown in Table I.

Figure 4 shows the expected sensitivity of $\theta_{13}$ as a function of $\Delta m^2_{13}$. Even though dominant term is $\theta_{13}$ for $\nu_\mu \to \nu_e$ appearance probability at 295km and neutrino energy of $\sim 0.6$ GeV, it is also depends on the other unknown parameter, $\delta_{CP}$. In any case of $\delta_{CP}$, expected sensitivity of $\sin^2 2\theta_{13}$ is 10 times or more smaller than current limit obtained by CHOOZ experiment around $\Delta m^2_{13} 2.5 \times 10^{-3}$eV$^2$.

2.4.2. $\Delta m^2_{23}$, $\theta_{23}$: $\nu_\mu$ Disappearance Measurement

We measure $\nu_\mu$ disappearance as both suppression in the total number of $\nu_\mu$ events observed at Super-Kamiokande.
Kamiokande has been in operation since 1996. In 2008, DAQ electronics and on-line computers will be upgraded and ready before neutrino beam starts.

3. Future Accelerator and Reactor Experiments

After the discovery of the neutrino oscillation and subsequent experiments, we have learned that a) neutrinos have small mass, b) mixing angles $\theta_{23}$ and $\theta_{12}$ are large, c) mixing angle $\theta_{13}$ is small (or zero). But we still have many questions like: 1) What is the value of third mixing angle $\theta_{13}$? 2) $\theta_{23}$ is exactly $45^\circ$ or not? 3) What is the ordering of the neutrino mass? 4) Is CP violated also in the lepton sector? To find the answers of these questions, many accelerator and reactor neutrino oscillation experiments are starting in these years in addition to T2K experiment.

3.1. Accelerator Experiments

Accelerator experiments measure $\theta_{23}$ and $\Delta m^2_{23}$ ($\sim \Delta m^2_{13}$) with very high precision in $\nu_{\mu} \rightarrow \nu_{\tau}$ disappearance channel and searches for $\theta_{13}$ in $\nu_{\mu} \rightarrow \nu_{e}$ appearance channel. MINOS experiment [6] with 735km baseline from Fermilab to Soudan started in May 2005 and disappearance measurement results are already published[7]. T2K experiment with 295km baseline from J-PARC and Kamioka starts physics run in 2009. By these long-baseline experiments, the mixing $\sin^2 2\theta_{23}$ and mass difference will be pinned down and the third mixing $\sin^2 2\theta_{13}$ will be searched for down to $\sim 0.01$. Another long-baseline neutrino oscillation experiment OPERA[8] with 732km baseline from CERN to CNGS started physics run in 2007. OPERA is designed to searches for $\nu_{\mu} \rightarrow \nu_{\tau}$ appearance channel by direct detection of $\nu_{\tau}$ interaction and expected to detect numbers of $\nu_{\tau}$ interactions within a few years of exposure.

3.2. Reactor Experiments

Reactor experiments searches for $\theta_{13}$ in $\bar{\nu}_e \rightarrow \bar{\nu}_x$ disappearance channel. Double-CHOOZ experiment[9] in France will start physics run in middle 2009, Dayabay experiment[10] in China will start with all detector by end of 2010, and RENO experiment[10] in Korea will start data taking in early 2010. All the experiments use gadolinium doped liquid scintillator to detect $\nu_e$ events and use same technique that put near detector at $\sim 300$m and far detector at 1 $\sim 2$km from nuclear power reactors. Though expected deficit of $\bar{\nu}_e$ of reactor dis-appearance experiment is quite small, this channel can measure $\theta_{13}$ free from $\delta_{CP}$ on contrary to the accelerator based appearance experiments. These reactor experiments are expected to
search $\sin^2 2\theta_{13}$ down to 0.01~0.03 after a few years of running.

### 3.3. CP Measurement

As a future expectation of early 2010’s, neutrino oscillation experiments mentioned in previous section will get knowledge about $\theta_{13}$. If we could get finite $\theta_{13}$ value, our target will change to next question 3) and 4). On the other hand, if we could get just small upper limit of $\sin^2 2\theta_{13}$, we still need to explore further small value. In any case, the measurement will become far precise and need huge statistics. Neutrino oscillation probability including CP phase $\delta$ and matter effects in the earth is shown in Figure 5. Two examples of oscillation probability in the case of $\sin^2 2\theta_{13} = 0.1$ (just below CHOOZ boundary) and 0.03 (around sensitivity limit of experiments shown in previous subsections) are shown in Figure 6.

To realize such a precise measurement with huge statistics, in addition to the improvement of accelerator power, several techniques of huge neutrino detectors are under study. Hyper-Kamiokande[13] is a gigantic water Cerenkov detector under study to be built in Kamioka. Here, we assume J-PARC accelerator power is upgraded to 1.7MW and expose neutrino beam to Hyper-Kamiokande at the same length of baseline with T2K. Expected $\nu_\mu \rightarrow \nu_e$ signal and backgrounds are shown in Table III. If $\delta_{CP}$ is non-zero value, $\nu_\mu \rightarrow \nu_e$ oscillation probability is different from $\nu_\mu \rightarrow \nu_e$ case. We can search $\delta_{CP}$ value by comparing the oscillation probabilities of neutrino and antineutrino case. Since the interaction cross-section with proton and neutron is smaller for anti-neutrino, we need longer exposure time for anti-neutrino run.

As another possible detector to explore $\delta_{CP}$, large liquid argon TPC detector is under study [12]. By measuring energy spectrum of lower energy neutrino than water Cerenkov threshold, we can measure $\delta_{CP}$ from a spectrum distortion of second oscillation maximum without anti-neutrino run. To measure it, longer baseline than current T2K baseline (295km) should be optimum. The study [12] suggests Okinoshima island as a possible site.

Before moving into CP measurement, we need to have knowledge about $\theta_{13}$. Getting results about $\theta_{13}$ by the experiments mentioned in subsections 3.1 and 3.2 as early as possible is one of most important requirement for neutrino oscillation physics in next \~5 years.

### 4. Summary

Next generation accelerator and reactor neutrino experiments aiming to measure finite value of $\theta_{13}$ are starting in a few years. Long baseline accelerator experiment T2K will start on Apr. 2009. If non-zero $\theta_{13}$ is observed, oscillation experiments should proceed to the next phase. The main goal of the next phase is the observation of CP violation in the neutrino sector. For the observation, we need precise measurement with huge statistics. The measurement of $\theta_{13}$ as soon as possible is necessary to determine the direction of the next phase experiments.

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\[ P(\nu_\mu \rightarrow \nu_e) = 4C_{13}^2 S_{13}^2 S_{23}^2 \left( 1 + \frac{2a \Delta m_{13}^2}{\sin^2 \Delta_{31}} \right) \cdot \sin^2 \Delta_{31} \]
\[ + \ 8C_{13}^2 S_{12} S_{13} S_{23} (C_{12} C_{23} \cos \delta - S_{12} S_{13} S_{23}) \cdot \cos \Delta_{32} \cdot \sin \Delta_{31} \cdot \sin \Delta_{21} \]
\[ \pm \ 8C_{13}^2 C_{12} S_{12} S_{13} S_{23} \sin \delta \cdot \sin \Delta_{32} \cdot \sin \Delta_{31} \cdot \sin \Delta_{21} \]
\[ + 4S_{12}^2 C_{13}^2 (C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12} C_{23} S_{12} S_{23} S_{13} \cos \delta) \cdot \sin^2 \Delta_{21} \]
\[ - 8C_{13}^2 S_{13}^2 S_{23}^2 \frac{\sin \delta}{4E_\nu} (1 - 2S_{13}^2) \cdot \cos \Delta_{32} \cdot \sin \Delta_{31} \]

Figure 5: Oscillation probability of \( \nu_\mu \rightarrow \nu_e \) (\( \bar{\nu}_\mu \rightarrow \bar{\nu}_e \)) where \( C_{ij} = \cos \theta_{ij} \), \( S_{ij} = \sin \theta_{ij} \), \( \Delta_{ij} = \Delta m_{ij}^2 \cdot L/4E_\nu \), \( L \) is neutrino flight length in km, \( E_\nu \) is neutrino energy in GeV, \( a = 2\sqrt{2}G_F N_e E_\nu \) and \( \delta \) is CP phase.

Figure 6: Oscillation probability in the function of neutrino energy \( E_\nu \) at neutrino flight length \( L=295 \) km, CP phase \( \delta = \pi/4 \), \( \sin^2 \theta_{23} = 1 \) and \( \sin^2 \theta_{13} = \) (left:)0.1, (right:)0.03. Black lines show total oscillation probability, red, cyan, magenta, green and blue lines shows each component of first, second, third, fourth and fifth term in Figure 5 respectively.

Figure 7: Schematic view of gigantic water Cerenkov neutrino detector Hyper-Kamiokande. Planning total and fiducial volumes are 1 Mega-ton and 0.54 Mega-ton, respectively. See [11] in detail.

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