

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 θ_{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 θ_{13} by observing ν_e appearance. Determining θ_{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 of quark sector.

Atmospheric and long baseline accelerator neutrino experiments already measured $\sin^2 2\theta_{23}$ and $|\Delta m_{23}^2|$ [1]. Solar and long baseline reactor neutrino experiments have measured $\sin^2 \theta_{12}$ [2]. However, as for the third mixing angle θ_{13} , only an upper limit has been determined [3]. Finite value of θ_{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 θ_{13} by appearance ($\nu_\mu \rightarrow \nu_e$) or disappearance ($\nu_e \rightarrow \nu_\mu, \nu_\tau$) oscillation channel.

If finite θ_{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 Cerenkov detector Super-Kamiokande is used as a far detector. The main physics goals of the experiment are precise measurement of oscillation parameters, Δm_{23}^2 and $\sin^2(2\theta_{23})$, in ν_μ disappearance channel and discovery of finite θ_{13} by observing ν_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 π^+ direction. We set

the off-axis angle to 2.5° in order to tune beam energy to be $0.6 \sim 0.7$ GeV which corresponds that we can measure oscillation maximum at 295km baseline when $\Delta m_{23}^2 = (2.2 \sim 2.6) \times 10^{-3} eV^2$.

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 ~ 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.

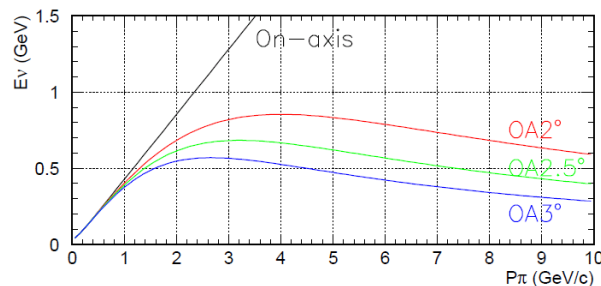


Figure 1: Off-axis angle dependence of mean neutrino energy.

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.

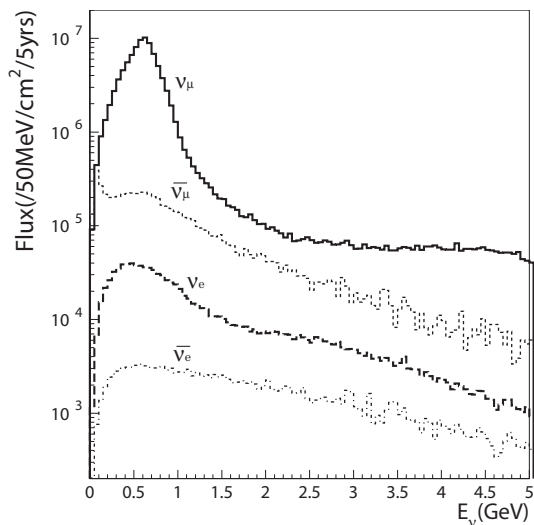


Figure 2: Expected neutrino flux at 295km

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 π^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.

2.3. Far Detector: Super-Kamiokande

The far detector Super-Kamiokande is a cylindrically shaped water Cerenkov detector. It consists 50 kton in total (22.5 kton fiducial volume) of pure water surrounded by 11127 20-inch photo multiplier tubes. We are able to identify particle property using the feature of Cerenkov ring image; shower-type ring for electron while sharp-edged ring for muon. The muon-electron particle separation is better than 99%. The uncertainty of the energy scale is $\sim 2\%$. Detailed description of Super-Kamiokande detector can be found in [4].

T2K neutrino events are selected from other background events by using timing information. To enable the selection, both beam time stamp at J-PARC and event time stamp at Super-Kamiokande are stamped by identical GPS systems. Beam timing information will be transferred to Super-Kamiokande immediately so that real-time GPS timing reduction is enable.

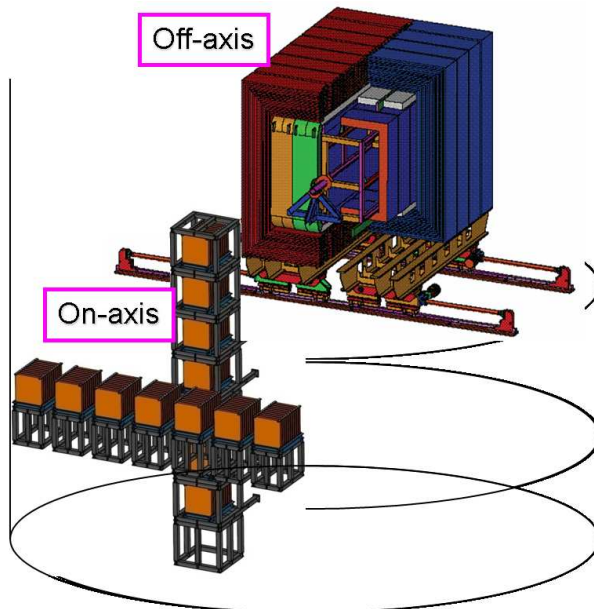


Figure 3: Near detectors placed at 280m downstream of proton target

2.4. Physics Prospect

2.4.1. θ_{13} : ν_e Appearance Measurement

We measure ν_e appearance signal in ν_μ beam by detecting Cerenkov ring of single electron from ν_e CCQE interaction in Super-Kamiokande.

Major backgrounds in the search are intrinsic ν_e in the beam and mis-identification to single electron of single π^0 production in NC interactions. The ν_e component in the beam is 0.4% at the peak of beam energy. The NC π^0 is mis-identified when one of two photons from π^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/π^0 separation cuts in order to further reduce NC π^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 θ_{13} as a function of Δm_{13}^2 . Even though dominant term is θ_{13} for $\nu_\mu \rightarrow \nu_e$ appearance probability at 295km and neutrino energy of ~ 0.6 GeV, it is also depends on the other unknown parameter, δ_{CP} . In any case of δ_{CP} , expected sensitivity of $\sin^2 2\theta_{13}$ is 10 times or more smaller than current limit obtained by CHOOZ experiment around $\Delta m_{13}^2 \sim 2.5 \times 10^{-3} eV^2$.

2.4.2. $\Delta m_{23}^2, \theta_{23}$: ν_μ Disappearance Measurement

We measure ν_μ disappearance as both suppression in the total number of ν_μ events observed at Super-

Table I Expected signal and background events in ν_e appearance measurement after T2K 5 year exposure, assuming $\delta_{CP} = 0$.

$\sin^2 2\theta_{13}$	Signal	Background in Super-K		
		ν_μ	Beam ν_e	Total
0.1	103	10	13	23
0.01	10	10	13	23

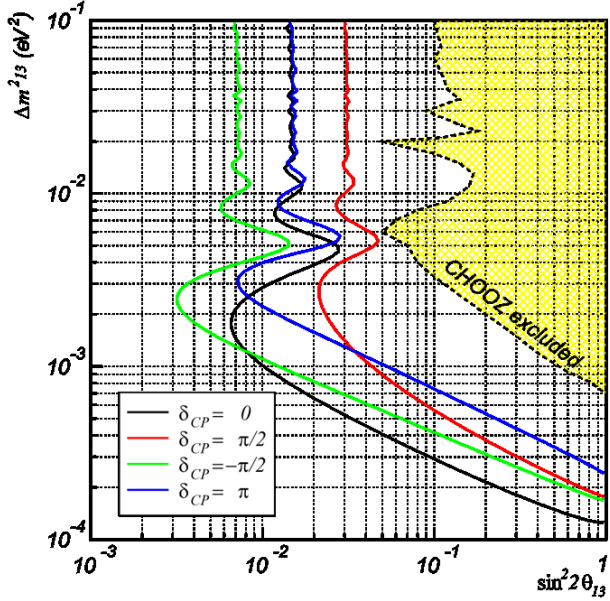


Figure 4: Sensitivity of θ_{13} search as a function of Δm_{13}^2 in four cases of δ_{CP} after T2K 5 years of exposure.

Kamiokande and a distortion of the energy spectrum compared to the expected spectrum of no oscillation, which extrapolated from the measurement at production point. We expect that our sensitivities for ν_μ disappearance are $\delta(\Delta m_{23}^2) < 1 \times 10^{-4} eV^2$ and $\delta(\sin^2 2\theta_{23}) \sim 1\%$ with 5 year of exposure.

2.5. Construction Status

Construction of accelerator complex in J-PARC is completed in 2008. Commissioning of Linac and 3 GeV RCS ash succeeded in January and November 2007. Then, commissioning of 50 GeV PS has succeeded in May 2008.

Neutrino beamline has been constructed since 2004. Civil construction has been finished and installation of super- and normal conducting magnets has been started. Manufacture and long term test of target and horn magnets are in progress and are on schedule. Commissioning of the neutrino beamline will be in April 2009.

Neutrino detectors at J-PARC are under construction and will be installed in 2009. Far detector Super-

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 subsequential experiments, we have learned that a) neutrinos have small mass, b) mixing angles θ_{23} and θ_{12} are large, c) mixing angle θ_{13} is small (or zero). But we still have many questions like: 1) What is the value of third mixing angle θ_{13} ? 2) θ_{23} is exactly 45° 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 θ_{23} and Δm_{23}^2 ($\sim \Delta m_{13}^2$) with very high precision in $\nu_\mu \rightarrow \nu_x$ disappearance channel and searches for θ_{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 ~ 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 ν_τ interaction and expected to detect numbers of ν_τ interactions within a few years of exposure.

3.2. Reactor Experiments

Reactor experiments searches for θ_{13} in $\bar{\nu}_e \rightarrow \bar{\nu}_x$ disappearance channel. Double-CHOOZ experiment[9] in France will start physics run in middle 2009, Daya bay 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 $\bar{\nu}_e$ events and use same technique that put near detector at $\sim 300m$ and far detector at $1 \sim 2km$ from nuclear power reactors. Though expected deficit of $\bar{\nu}_e$ of reactor disappearance experiment is quite small, this channel can measure θ_{13} free from δ_{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 θ_{13} . If we could get finite θ_{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 δ 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[11] 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 II. If δ_{CP} is non-zero value, $\nu_\mu \rightarrow \nu_e$ oscillation probability is differ from $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ case. We can search δ_{CP} value by comparing the oscillation probabilities of neutrino and anti-neutrino 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 δ_{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 δ_{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 is a possible site.

Before moving into CP measurement, we need to have knowledge about θ_{13} . Getting results about θ_{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 θ_{13} are

Table II expected $\nu_\mu \rightarrow \nu_e$ signal and backgrounds for future δ_{CP} search assuming 2.2year ν_μ and 7.8year $\bar{\nu}_\mu$ exposure by upgraded 1.7MW accelerator at J-Parc to 0.54 Mega-ton fiducial volume water Cerenkov detector placed at Kamioka.

	$\nu_\mu \rightarrow \nu_e$ signal		Background			
	$\delta_{CP} = 0$	$\delta_{CP} = \pi/2$	ν_μ	$\bar{\nu}_\mu$	ν_e	$\bar{\nu}_e$
ν_μ 2.2yr	1049	579	354	26	379	10
$\bar{\nu}_\mu$ 7.8yr	1050	1493	443	610	241	415

starting in a few years. Long baseline accelerator experiment T2K will start on Apr. 2009. If non-zero θ_{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 θ_{13} as soon as possible is necessary to determine the direction of the next phase experiments.

Acknowledgments

The author thanks the organizers of the Flavor Physics & CP Violation (FPCP) 2008 conference for the invitation to present this talk and hospitality of the conference. This work was partly supported by the Grant-in-Aid for Scientific Research, Japan Society for the Promotion of Science.

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$$\begin{aligned}
P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) &= 4C_{13}^2 S_{13}^2 S_{23}^2 \cdot \left(1 + \frac{2a}{\Delta m_{13}^2} (1 - 2S_{13}^2)\right) \cdot \sin^2 \Delta_{31} \\
&+ 8C_{13}^2 S_{12} S_{13} S_{23} (C_{12} C_{23} \cos \delta - S_{12} S_{13} S_{23}) \cdot \cos \Delta_{32} \cdot \sin \Delta_{31} \cdot \sin \Delta_{21} \\
&\pm 8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin \delta \cdot \sin \Delta_{32} \cdot \sin \Delta_{31} \cdot \sin \Delta_{21} \\
&+ 4S_{12}^2 C_{13}^2 (C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12} C_{23} S_{12} S_{23} S_{13} \cos \delta) \cdot \sin^2 \Delta_{21} \\
&- 8C_{13}^2 S_{13}^2 S_{23}^2 \cdot \frac{aL}{4E_\nu} (1 - 2S_{13}^2) \cdot \cos \Delta_{32} \cdot \sin \Delta_{31}
\end{aligned}$$

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_ν is neutrino energy in GeV, $a = 2\sqrt{2}G_F N_e E_\nu$ and δ is CP phase.

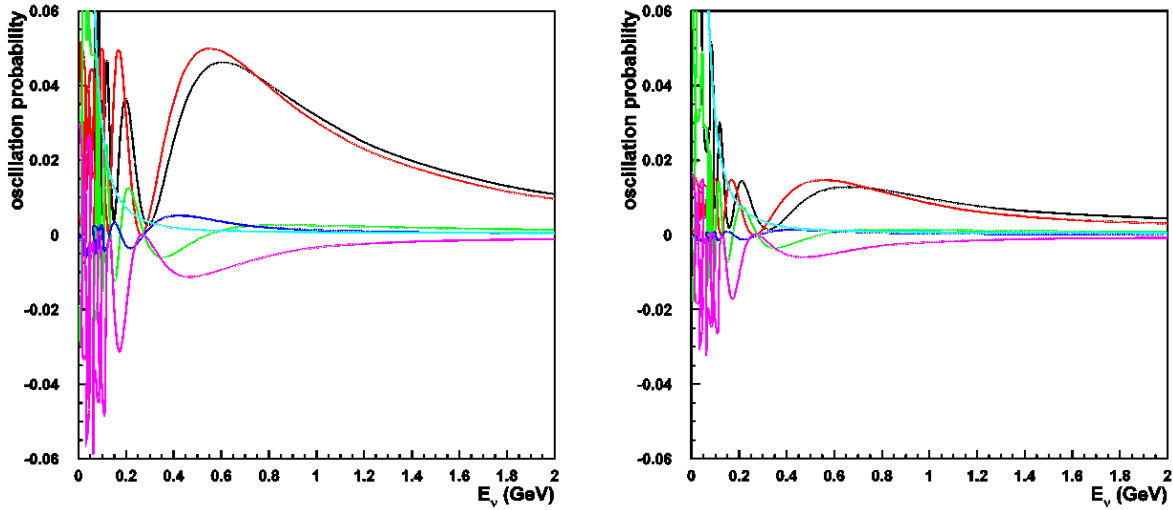


Figure 6: Oscillation probability in the function of neutrino energy E_ν at neutrino flight length $L=295\text{km}$, CP phase $\delta = \pi/4$, $\sin^2 2\theta_{23} = 1$ and $\sin^2 2\theta_{13}$ =(left:)0.1, (right:)0.03. Black lines show total oscillation probability, red, cyan, magenta, green and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

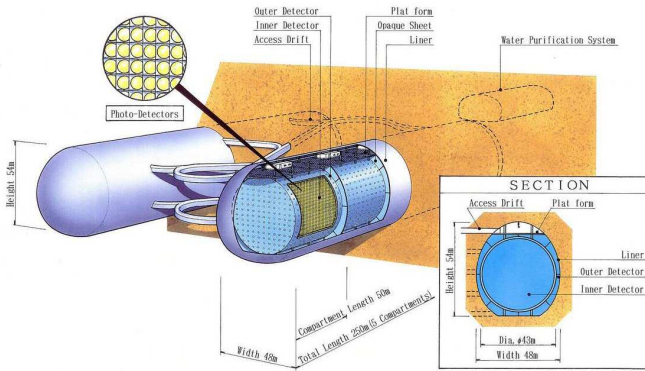


Figure 7: Schematic view of gigantic water Cerenkov neutrino detector Hyper-Kamiokande. Planning total and fiducial volumes are 1 Mega-ton and 0.54 Mega-ton, respectively. See [11] in detail.