The T2K Neutrino Oscillation Experiment and Possible Future Projects

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The Tokai to Kamioka (T2K) experiment is a next generation long baseline neutrino oscillation experiment utilising the Japan Proton Accelerator Research Complex (J-PARC) high intensity proton synchrotron. After a brief introduction of the current understanding of neutrino mixing, the T2K experiment, its current status and the expected physics results are presented. Then, possibilities for future neutrino oscillation experiments utilising J-PARC are discussed.

1. Introduction

Neutrino oscillations have been observed via their disappearance signature in atmospheric and long baseline accelerator produced ν_μ and solar and reactor produced ν_e and $\bar{\nu}_e$. These oscillations can be readily explained by the Maki Nakagawa Sakata (MNS) mixing matrix which relates the neutrino mass Eigen states to the flavour Eigen states:

$$\overbrace{\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}}^{\text{Flavour}} = \underbrace{\begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}}_{\text{Atmo's \& Long BL}} \overbrace{\begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta} & 0 & c_{13}\end{pmatrix}}^{\text{Unknown}}$$
$$\times \underbrace{\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}}_{\text{KamLAND \& Solar}} \overbrace{\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}}^{\text{Mass}}, \quad (1)$$

where $s_{ij} \equiv \sin\theta_{ij}$ and $c_{ij} \equiv \cos\theta_{ij}$. The KamLAND experiment observing $\bar{\nu}_e$ from reactors and observations of deficits of solar neutrinos provide measurements of $\sin^2 2\theta_{12}$ and the mass difference Δm^2_{12}. Observations of atmospheric ν_μ deficits and angular distributions and long baseline accelerator produced neutrino experiments have provided measurements of $\sin^2 2\theta_{23}$ and the mass difference squared Δm^2_{23}. There are still significant unanswered questions. The world average for $\sin^2 2\theta_{23}$ is consistent with unity: but is this it's true value? Ie. is the mixing maximal? The Tokai to Kamioka (T2K) experiment will address this question by refining the ν_μ disappearance analysis of earlier experiments providing a precision measurement of $\sin^2 2\theta_{23}$. The CHOOZ reactor experiment tells us that $\sin^2 2\theta_{13}$ is small (< 0.13, 90% CL), but is it really non-zero? T2K will endeavour to discover a non-zero $\sin^2 2\theta_{13}$ by searching for $\nu_\mu \rightarrow \nu_e$ oscillations.

2. T2K

2.1. Neutrino Beam

The T2K experiment is a "Next generation" long baseline neutrino oscillation experiment. A ν_μ beam will be produced using the newly constructed proton synchrotron at Japan Proton Accelerator Research Complex (J-PARC) in Tokai on the East coast of Japan. The neutrinos will propagate 295 km through the earth to Kamioka where they will be detected by the existing Super-Kamiokande (SK) water Cerenkov detector. The experiment is scheduled to start in April 2009 and is planned to run for five years with a beam power of 0.75 MW. This represents approximately a factor of 100 increase in data sample of the KEK to Kamioka (K2K) experiment.

The neutrino beam will be created by striking a carbon target with an intense proton beam producing pions. A series of three magnetic horns selects and focuses the positive pions into a 110 m helium filled decay volume — where they decay — producing μ^+ and ν_μ. Just downstream of the decay volume the muon beam's intensity, profile and direction are monitored providing information on the same parameters for the accompanying neutrinos.

Located two hundred and eighty metres from the target are a pair of "Near Detectors". These detectors are designed to monitor the neutrino beam itself. The neutrino beam then travels 295 km to the Super-Kaimokande detector. A novel feature of the beam line is that it utilises an "off-axis" configuration: the neutrino beam is not aimed directly at Super-K, but 2.5° from it. A cartoon of the configuration is shown in Fig. 1. This configuration utilises a nice feature of the pion decay kinematics. The neutrino energy is given by

$$E_\nu = \frac{m_\pi^2 - m_\mu^2}{2(E_\pi - p_\pi \cos\theta_{\mathrm{OA}})}, \quad (2)$$

where all parameters are in the laboratory frame and θ_{OA} is the angle between the neutrino and pion flight directions. The decay is illustrated in Fig. 2. Figure 3 shows Eq. 2 plotted for different θ_{OA} demonstrating how selecting neutrinos at non-zero angles from the

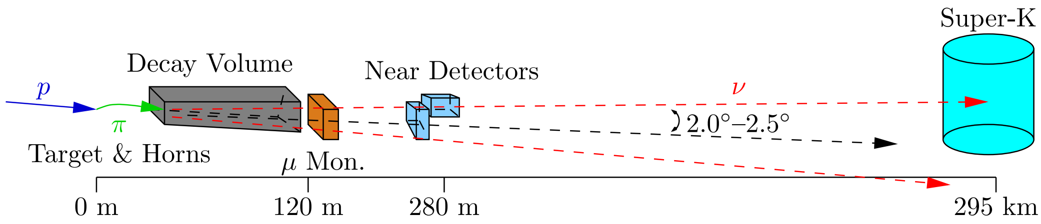

Figure 1: Configuration of the T2K neutrino beam indicating the beam monitors and detectors and the off-axis configuration.

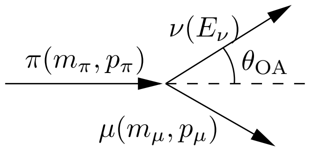

Figure 2: Pion decay kinematics in the laboratory frame.

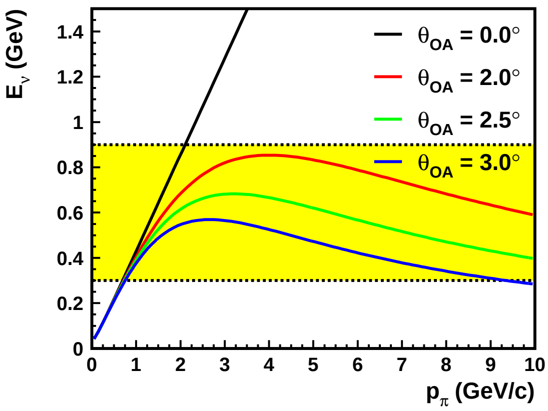

Figure 3: Neutrino beam energy as a function of pion energy for different off axis angles.

pion beam direction provides an almost monochromatic neutrino beam energy. T2K is setup to run with $\theta_{\rm OA}$ =2.5° which selects 600 MeV to 700 MeV neutrinos placing the first neutrino oscillation maximum at Super-K for $\Delta m^2 = 2.5 \times 10^{-3}$ eV$^2/c^4$.

2.2. Schedule

Commissioning of the J-PARC linac, Rapid Cycling Syncrotron (RCS) and Main Ring (MR) began in 2006, 2007 and 2008 respectively. All components excluding the fast extraction kickers of the MR were installed as of April 2008. Closed orbit in the MR was established in May 2008 and the fast extraction kicker installation is scheduled for June 2008. Acceleration of the beam in the MR to 30 GeV and fast extraction to the neutrino beamline are scheduled for December 2008 and April 2009.

2.3. Apparatus

The apparatus of the T2K experiment consist of four major parts: The primary beamline, the secondary beamline, the near detectors and the far detector.

2.3.1. Primary Beamline

This first section of the primary beamline focusses the protons from the MR in preparation for the for transportation through the curved Super Conducting (SC) or arc section which bends the beam almost 90° towards the target. The SC magnets in the arc section are combined dipole/quadrapole magnets consisting of 14 doublets. The final section of the primary beamline defocuses the beam and delivers it to the target. The beamline incorporates 21 position, 19 profile, 5 intensity and 50 beam loss monitors.

2.3.2. Secondary Beamline

The secondary beamline consists of a helium vessel containing a graphite target located in the first of three "horn" magnets designed to focus the pions produced when the proton beam strikes the target. Horn operation has been tested up to 320 kA. The facility is complete with a fully remote crane and maintenance area to allow horn and target replacement in the event of failure of any component. Civil construction was finished in May 2008. Downstream of the target station is a 110 m long helium filled decay volume which ends with a hadron absorber consisting of water cooled graphite blocks, behind which is an array of ionisation chambers and silicon PIN diodes which monitor the direction and profile of the muons created from the pion decays.

2.3.3. Neutrino Detectors

Two near detectors: on-axis and off-axis will be located in a pit 280 m downstream of the target. The on-axis detector, INGRID, consists of a 10 m by 10 m configuration of stacks of scintillators interleaved with iron sheets. This detector, to be completed by April 2009, is designed to directly monitor the ν_μ beam profile and direction with a resolution of 0.18 mrad. The off-axis detector, ND280, is designed to measure the neutrino flux in the direction of SK for both ν_μ

and ν_e utilising a fine grained tracker to accurate reconstruction of Charged Current Quasi-Elastic (CC-QE) events. The detector will also be capable of measuring the relative CC-QE to Charged Current NonQuasi-Elastic (CC-nQE) cross sections and will have calorimeters which will be utilised to measure the neutral current π^0 production rate (background source for the $\nu_\mu \to \nu_e$ search). The Near Detector at 280 metres (ND280) will be completed in the second half of 2009.

Located 295 km from J-PARC is the far detector: the 22.5 kt fiducial volume water Cerenkov detector SK. SK was fully re-populated with photomultiplier tubes (PMTs) in 2006, now with a total of 11146 and 1885 PMTs in the inner and outer volumes respectively and will have new electronics installed in September 2008.

2.4. Expected Physics Results

The survival probability for the neutrinos produced in T2K is given by

$$P(\nu_\mu \to \nu_\mu) \simeq 1 - \sin^2 2\theta_{23} \sin^2 \left(\frac{1.27 \Delta m^2_{23} L}{E_\nu} \right), \quad (3)$$

where L and E_ν are the neutrino flight length and energy. As such the observed number of ν_μ events at SK as a function of E_ν for the fixed $L = 295$ km can be fitted to Eq.(3) to extract θ_{23} and Δm^2_{23}.

At SK the neutrino energy can be reconstructed though CC-QE interactions as illustrated in Fig. 4. From this interaction in SK, (E_μ, θ) are extracted and

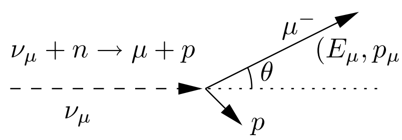

Figure 4: Charged Current Quasi-Elastic (CC-QE) interaction

used to calculate the incident ν_μ energy from the kinematics of the interaction:

$$E_\nu = \frac{m_n E_\mu - m_\mu^2/2}{m_n - E_\mu + p_\mu \cos\theta}. \quad (4)$$

The expected number of neutrinos at the ND280 and SK can be given by $N_{\rm ND} = \phi_{\rm ND}\sigma_{\rm ND}$ and $N_{\rm SK} = \phi_{\rm SK}\sigma_{\rm SK}P_{\rm osc}$ respectively. Of these $\sigma_{\rm SK}$, $\sigma_{\rm ND}$ and $\phi_{\rm ND}$ are studied with the ND280. Treating the fluxes as a ratio: $R_{N/F} = \frac{\phi_{\rm SK}}{\phi_{\rm ND}}$, the number of events can be predicted: $N^{\rm pred}_{\rm SK} = N^{\rm obs}_{\rm ND} R_{N/F} \frac{\sigma_{\rm SK}}{\sigma_{\rm ND}}$. To calculate the so called near-far ratio, $R_{N/F}$, the hadron production in the T2K target needs to be well understood. This will studied with the SHINE experiment (NA49 upgraded to NA61) at CERN. SHINE runs with a proton beam on carbon target with conditions tuned to match those of T2K. The detector has good tracking and particle identification enabling discrimination between $\pi^\pm$ and $K^\pm$ and reconstruction of K^0.

The approved total integrated beam power to T2K is 0.75 × 1500 h. It is expected that this will be delivered within five years of operation. The following sensitivities assume this integrated beam power.

2.4.1. ν_μ disappearance: Precision θ_{23} and Δm^2_{23} measurements

Figure 5 shows the expected neutrino energy spectrums and NonQuasi-Elastic backgrounds for the case of no oscillations and oscillations with $\Delta m^2_{23} = 2.5 \times 10^{-3}$ eV^2. Studies have shown that the systematic uncertainties in the flux prediction can be controlled to better than 25% resulting in the final uncertainties in θ_{23} and Δm^2_{23} being statistically limited. The resulting expected achieved sensitivities are $\delta(\sin^2 2\theta_{23}) \simeq 0.01$ and $\delta(\Delta m^2_{23}) < 10^{-4}$ eV^2.

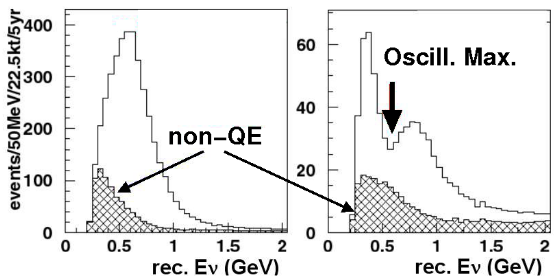

Figure 5: Reconstructed energy spectrums for ν_μ disappearance analysis. The hatched areas show the NonQuasi-Elastic backgrounds. Left plot shows the case of no oscillations, the right plot shows oscillations with $\Delta m^2_{23} = 2.5 \times 10^{-3}$ eV^2. The dip caused by the first oscillation maximum is indicated. The position of the dip is governed by Δm^2_{23} and the depth by $\sin^2 2\theta_{23}$.

2.4.2. ν_e appearance: non-zero θ_{13}

Utilising the electron identification abilities of SK with a background estimation error of 10% T2K will be able to place limits of $\sin^2 2\theta_{13} < 0.008$ (90% C.L.) for: $\delta_{\rm CP} = 0$, $\Delta m^2_{13} = 2.5 \times 10^{-3}$ eV^2 and $\sin^2 2\theta_{23} = 1$. Or better than $\sin^2 2\theta_{13} < 0.02$ (90% C.L.) for any value of $\delta_{\rm CP}$, representing a factor of ten improvement of the CHOOZ limits. Sensitivity contours for various values of $\sin^2 2\theta_{23}$ in the $\delta_{\rm CP}$-$\sin^2 2\theta_{13}$ plane are shown in Fig. 6.

3. Possible Future Projects

If a significant $\nu_\mu \to \nu_e$ signal is seen with T2K there will be strong motivation carry out further studies utilising the neutrino beamline at J-PARC. The

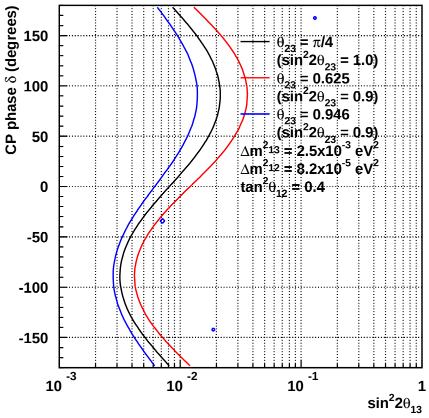

Figure 6: Sensitivity contours in the $\sin^2 2\theta_{13}$-$\delta_{\rm CP}$ for various values of $\sin^2 2\theta_{23}$.

goals of such studies include refining the $\nu_\mu \to \nu_e$ appearance measurement providing more precise information on $\sin^2 2\theta_{13}$ and to try *CP* violation physics studies. To achieve such goals it will be necessary increase the neutrino beam intensity and hence the proton beam intensity. Additionally it will be vital to improve the far detector in terms of target mass and/or technology and the baseline and beam angle configuration.

With the higher statistics from such an upgraded experiment it is important to consider the $\nu_\mu \to \nu_e$ transition probability in some detail. An expansion of the analytic expression for $P(\nu_\mu \to \nu_e)$ around the small parameters $\alpha \equiv \frac{\Delta m^2_{21}}{\Delta m^2_{31}}$ and $\sin 2\theta_{13}$, yields[1]:

$$P(\nu_\mu \to \nu_e) = \sin^2 2\theta_{13} T_1 + \alpha \sin 2\theta_{13} \overbrace{(T_2 - T_3)}^{\text{Interference}} + \alpha^2 T_4. \quad (5)$$

Where:

$$\begin{aligned}
T_1 &= \sin^2\theta_{23} \frac{\sin^2[(A-1)\Delta]}{(A-1)^2}, \quad \leftarrow \text{Atmospheric} \\
T_2 &= \cos\delta_{\rm CP} \sin 2\theta_{12} \sin 2\theta_{23} \cos\Delta \\
&\quad \times \frac{\sin(A\Delta)}{A} \frac{\sin[(A-1)\Delta]}{A-1}, \\
T_3 &= \sin\delta_{\rm CP} \sin 2\theta_{12} \sin 2\theta_{23} \sin\Delta \\
&\quad \times \frac{\sin(A\Delta)}{A} \frac{\sin[(A-1)\Delta]}{A-1}, \\
T_2 - T_3 &= \sin 2\theta_{12} \sin 2\theta_{23} \cos(\Delta + \delta_{\rm CP}) \\
&\quad \times \frac{\sin(A\Delta)}{A} \frac{\sin[(A-1)\Delta]}{A-1}, \\
T_4 &= \cos^2\theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(A\Delta)}{A^2}. \quad \leftarrow \text{Solar}
\end{aligned} \quad (6)$$

And:

$$A \equiv \frac{2EV}{\Delta m^2_{31}}, \quad \Delta \equiv \frac{\Delta m^2_{31} L}{4E}, \quad (7)$$

where V is the potential seen by a neutrino passing through the earth and as such A is known as the "matter effect" term. In the representation of Eq. 5 and Eq. 6 it is instructive to consider the contributing terms in the energy region of the T2K neutrino beam, $\lesssim$ 1 GeV. T_1, the "atmospheric" term is the dominant component driving the oscillation with period about double the length of the T2K baseline. T_4, the "solar" term is not related to $\sin 2\theta_{13}$ and has orders of magnitude longer period and such plays no relevant part in the following. The T_2 and T_3 terms are 90°out of phase, and when combined to $T_2 - T_3$, $\delta_{\rm CP}$ introduces a phase offset to the oscillation which when combined into the full oscillation probability can appear as a small change in the oscillation amplitude. It is also important to note that when replacing neutrinos with antineutrinos the $\delta_{\rm CP}$ is replaced with $-\delta_{\rm CP}$. The effects of $\delta_{\rm CP}$ to $P(\nu_\mu \to \nu_e)$ are illustrated in Fig. 7. Considering these issues it can be seen that

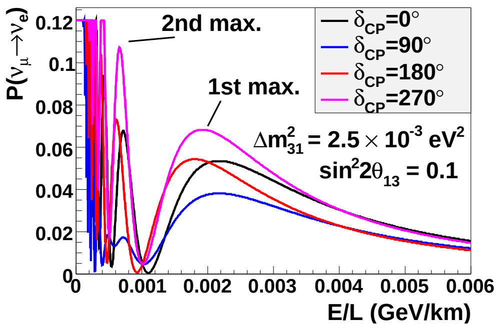

Figure 7: $P(\nu_\mu \to \nu_e)$ as a function of E/L for different values of $\delta_{\rm CP}$. The gross amplitude is determined by $\sin^2 2\theta_{13}$, but the value of $\delta_{\rm CP}$ changes the relative amplitude of the first and second maxima.

$\delta_{\rm CP}$ could be measured by an experiment using the J-PARC beamline if it could observe both the first and second oscillation maximum, or run with both neutrino and anti-neutrino beams. Both maximums can be observed by varying E/L, by either using two different baselines L_1 and L_2 or by varying the energy — recalling that the neutrino energy increases (and becomes less monochromatic) as the off-axis angle decreases. With this in mind it is instructive to consider Fig. 8 showing a map with off-axis angle contours for the J-PARC neutrino beam on the surface of the earth.

3.1. Okinoshima

Figure 8 shows the island of Okinoshima 658 km from J-PARC at a small off-axis angle of about 0.76°. The small off-axis angle provided by this location results in significant neutrino beam energy spread allowing a detector to observe not only the first but also the second oscillation maximum assuming that it had sufficiently good energy resolution below 1 GeV. As

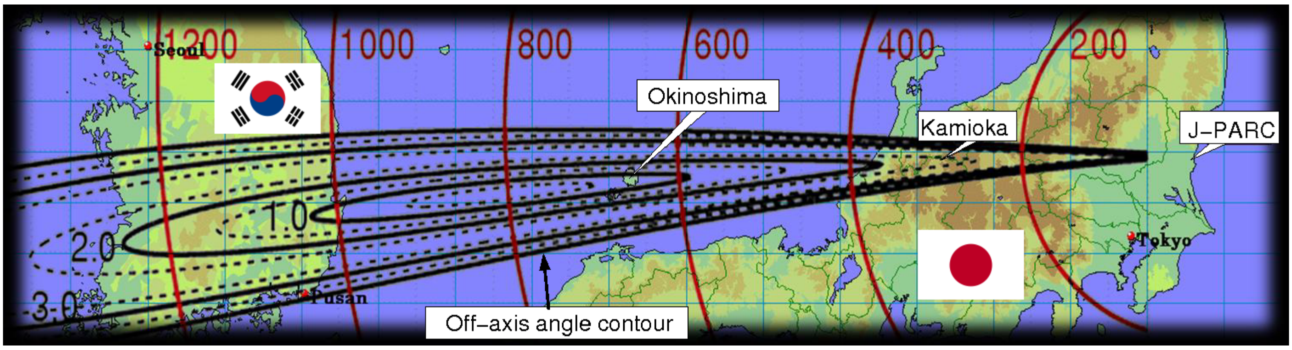

Figure 8: Map with off-axis angle and distance from production point contours for the J-PARC neutrino beam.

such it is proposed to place a Liquid Argon Time Projection Chamber (TPC)[2] on Okinoshima[3]. Such a detector is a precision device with excellent energy and spacial resolution. The spatial resolution that could be achieved would be able to significantly suppress the dominant π^0 background in ν_e reconstruction. Simulations with a 100 kt fiducial mass, $\sigma(E_\nu) = 100$ MeV, 5 years with a ν_μ beam and an input value of $\sin^2 2\theta_{13}$ =0.03 yields the distributions and allowed regions in the $\sin^2 2\theta_{13}$-$\delta_{\rm CP}$ plane shown in Fig. 9.

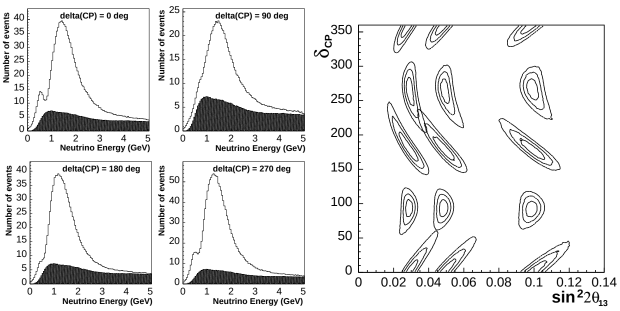

Figure 9: Very preliminary Okinoshima simulation results. The left plots show the energy spectra for (clockwise from top left) $\delta_{\rm CP} = 0°$, $90°$, $270°$ and $180°$. The right plot shows C.L.=67%, 95% and 99.7% allowed regions in the $\sin^2 2\theta_{13}$-$\delta_{\rm CP}$ plane. Twelve allowed regions are overlaid for the twelve combinations of $\sin^2 2\theta_{13} = 0.1$, 0.05, 0.02 and $\delta_{\rm CP} = 0°$,$90°$, $270°$ and $180°$.[3]

3.2. Kamioka: "Hyper-K"

The Hyper-K project is a plan to build a new 1000 kt ($\simeq$ 500 kt fiducial) volume Water Cerenkov detector at the Kamioka site. The massive volume — approximately 24 times larger that SK — would be realised using two 500 kt chambers illustrated in Fig. 10, with a total of 0.2×10^6 PMTs. Simulation studies[4] assuming 2.2 years of ν_μ and 7.8 years of $\bar{\nu}_\mu$ running with $\sin^2 2\theta_{13} = 0.1$ yield the distributions in

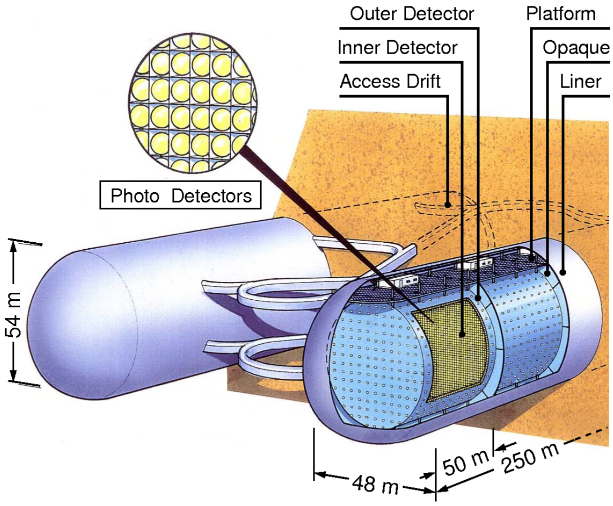

Figure 10: The proposed Hyper-K water Cerenkov detectors.

Fig. 11 and exclusion regions in Fig. 12.

3.3. Korea: "T2KK"

Inspection of Fig. 8 shows that the J-PARC neutrino beam extends to South Korea with baselines from 1000 km to 1250 km and off-axis angles from 1.0° to 4.0°. Selecting a baseline and off-axis angle of 1000 km and 2.5° would place a detector at the second neutrino oscillation maximum. Hence the idea is to place one of the Hyper-K detectors at Kamioka and one in Korea. Preliminary simulations[5] with five years ν_μ beam and five years $\bar{\nu}_\mu$ beam with an input value of $\sin^2 2\theta_{13} = 0.04$ yields the distributions in Fig. 13 and allowed regions in the $\sin^2 2\theta_{13}$-$\delta_{\rm CP}$ plane shown in Fig. 14

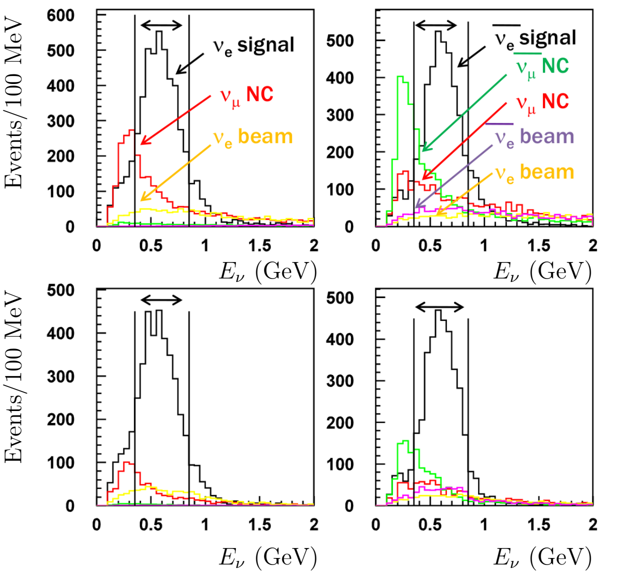

Figure 11: Hyper-K reconstructed energy distributions. The left plots are for ν_μ beam and the right plots for $\bar{\nu}_\mu$ beam. The upper and lower plots show the distributions before and after final analysis cuts respectively.

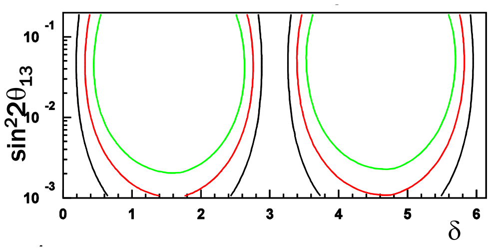

Figure 12: Hyper-K *CP* violation sensitivity plots. Contours indicate 1σ, 2σ and 3σ regions in the $\sin^2 2\theta_{13}$-$\delta_{\rm CP}$ plane.

4. Summary

The T2K experiment will utilise a new accelerator facility, J-PARC delivering statistics two orders of magnitude above those of K2K. An off-axis beam configuration will be utilised providing a narrow neu-

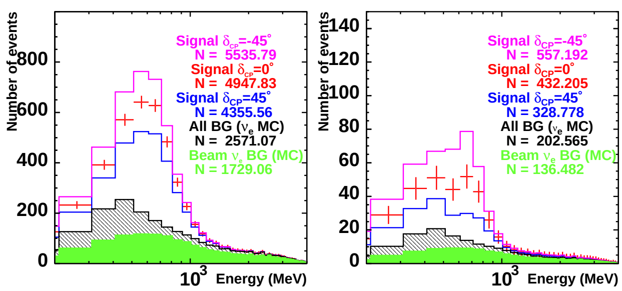

Figure 13: T2KK reconstructed neutrino energy distributions for Kamioka (left) and Korea (right).

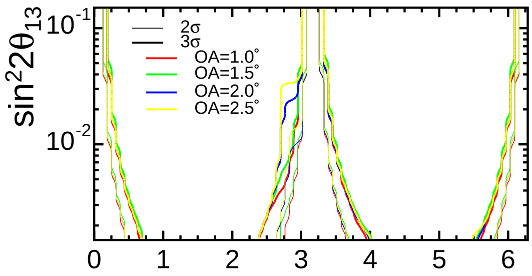

Figure 14: T2KK *CP* violation sensitivity plots. Narrow and bold lines indicate 2σ and 3σ regions. The different colours represent different off-axis angles and indicate no strong preference in choice of angle.

trino energy spectrum tuned to the oscillation maximum. The beam will be monitored by an extensive suite of detectors at the production site and will utilise the well established SK as the far detector. T2K will search for ν_e appearance with an order magnitude improvement on $\sin^2 2\theta_{13}$ sensitivity over current limits and will perform precision measurements of ν_μ disappearance with estimated uncertainties of $\delta(\sin^2 2\theta_{23}) \simeq 0.01$ and $\delta(\Delta m^2_{23}) < 10^{-4}\ eV^2$. Construction of the T2K facility at J-PARC is well underway with neutrino beam commissioning to begin in April 2009. If a sizable $\nu_\mu \to \nu_e$ signal is observed it is planned to upgrade the beam power and pursue one of the promising detector options under study to pursue *CP* physics studies in the neutrino sector.

References

1 Evgeny Khakimovich Akhmedov, Robert Johansson, Manfred Lindner, Tommy Ohlsson, and Thomas Schwetz. Series expansions for three-flavor neutrino oscillation probabilities in matter. *JHEP*, 04:078, 2004.
2 A. Rubbia. Experiments for CP-violation: A giant liquid argon scintillation, Cerenkov and charge imaging experiment? 2004.
3 A. Badertscher et al. A Possible Future Long Baseline Neutrino and Nucleon Decay Experiment with a 100 kton Liquid Argon TPC at Okinoshima using the J-PARC Neutrino Facility. 2008.
4 Kenji Kaneyuki. CP violation Physics at a J-PARC Beam - Water Cherenkov Detector. Talk at NP08.
5 Fanny Dufour. T2KK. Talk at NP08.