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Summary of the Latest Results and Future Prospects from the T2K Experiment

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Abstract. The T2K long-baseline experiment is located in Japan and is designed to study oscillations of muon neutrinos. T2K obtains a beam of muon neutrinos peaked at 0.6 GeV that are produced at J-PARC accelerator complex by converting a beam of 30-GeV protons hitting a graphite target. Upon traveling 295 km, neutrinos are detected by the Super-Kamiokande (SK) water Cherenkov detector. Located at 280 m from the target, the near detector complex (ND280) provides information about un-oscillated neutrino flux, beam stability and interaction cross-sections. The T2K experiment observed electron neutrino appearance at SK with the significance of 7.3 $\sigma$ and measured the associated oscillation parameter $\theta_{13}$ for both normal and inverted mass hierarchies. In addition, by looking at muon neutrino disappearance T2K provided improved measurements of the $\theta_{23}$ and $\Delta m^2_{32}$ parameters. The results of these measurements are presented as well as a brief summary of the selected neutrino cross-section measurements. Future prospects of the T2K experiment are discussed.

1. Introduction

Neutrinos play an inherent role in weak interaction processes of the standard model of particle physics. They participate in both charged current (CC) and neutral current (NC) interactions. The flavour of neutrino is assigned based on a charged lepton it produces in a CC interaction: an electron neutrino (or $\nu_e$) produces an electron, a muon neutrino (or $\nu_\mu$) produces a muon, and a tau neutrino (or $\nu_\tau$) produces a tau lepton.

Over the course of the past 30 years, it has been experimentally confirmed that neutrinos change from one flavour to another as they propagate. This transition in flight, called neutrino oscillations, can be explained by the quantum mechanical mixing between the flavour and mass eigenstates, and thus it is an evidence that neutrinos have mass. In general case, the probability of neutrino transition from one flavor to another depends on the mixing matrix elements, the propagation distance, the energy and the mass squared difference between the mass states (the squared-mass splittings). The mixing is given by so called Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix. For convenience and historical reasons this matrix is split into 3 parts, and written as follows:

$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{+i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

(1)
Figure 1. Propagation path of the muon neutrinos from J-PARC to the far detector.

The first part, involving the $\theta_{23}$ angle is associated with the disappearance (via oscillation) of the muon neutrinos produced in the atmosphere by cosmic ray interactions. The second part containing $\theta_{13}$ and $\delta_{CP}$ phase is relevant in the case of long baseline accelerator and reactor experiments, and the last part with $\theta_{12}$ is measured in the oscillations of the solar neutrinos. Most of the parameters in this matrix have been determined with relatively good precision by now: $\sin^2 2\theta_{12} = 0.857 \pm 0.024$, $\sin^2 2\theta_{23} > 0.95$ and $\sin^2 2\theta_{13} = 0.095 \pm 0.010$. The values of the squared-mass splittings are: $\Delta m^2_{21} = (7.5 \pm 0.20) \times 10^{-5}$ eV$^2$ and $|\Delta m^2_{32(13)}| = (2.32^{+0.12}_{-0.08}) \times 10^{-3}$ eV$^2$. In this formalism, there are two independent squared-mass splittings, $\Delta m^2_{21}$ and $\Delta m^2_{32}$ or $\Delta m^2_{13}$ and, since the sign of the latter two is not known, there are two possibilities: normal hierarchy (NH) or inverted hierarchy (IH). The questions of the mass hierarchy and of the value of the $\delta_{CP}$ phase remain open in the neutrino oscillation physics.

2. The T2K Experiment

The Tokai-to-Kamioka (T2K) experiment has been put together as a collaboration of 59 institutions from 11 countries$^1$. To study neutrino oscillations a beam of muon neutrinos is produced by the J-PARC proton accelerator located in Tokai on the east coast of Honshu island in Japan. Having traveled underground for 295 km, neutrinos are detected by the Super-Kamiokande detector inside the Kamioka mine on the west coast of the island. The schematic view of the experiment is shown in Figure 1. Every part of the T2K experiment contributes to the results of the neutrino oscillation studies presented later. The components of the experiment will be described in the subsections below.

2.1. The Beamline of T2K

The T2K beamline consists of the primary and secondary beamlines. The primary beamline serves to steer the 30-GeV proton beam extracted from the J-PARC accelerator Main Ring at 2-3 Hz into the secondary beamline. A group of eight circulating proton bunches called a spill is extracted within each single turn of the beam. The bunch timing information is very important for discriminating various backgrounds in all of the detectors downstream of the beamline including the far detector which receives GPS stamps of every spill over a private network using GPS technology with the precision of 50 ns.

The secondary beam line consists of a graphite target, a system of three magnets called "horns", a decay volume, a beam dump and a muon monitor. Nuclear interactions in the target produce a beam of secondary particles consisting of charged pions and kaons mostly. Polarity of the horns can be switched to focus positively (negatively) charged secondaries before they proceed along the 96-m-long decay volume producing a beam of muon neutrinos (anti-neutrinos). All other particles except for the neutrinos and energetic (> 5 GeV) muons are stopped by the

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$^1$ The United Kingdom, France, Spain, Italy, Switzerland, Germany, Poland, Russia, Japan, Canada and the United States
beam dump, a 3.2-m layer of graphite and 2.4-m layer of iron. The muons are detected by the muon monitor and used to check the beam stability.

An essential feature of the T2K experiment is the geometry of its beamline relative to the far detector. The direction of the SK detector is off by 2.5° with respect to the main beam axis. From the decay reaction kinematics, it follows that the resulting energy distribution of the neutrino flux is narrow and peaked at 0.6 GeV corresponding to the energy which maximizes the probability of observation of $\nu_e$ in the case of normal hierarchy or alternatively minimizes the $\nu_\mu$ survival probability at SK.

Prediction of the $\nu_\mu$ flux at SK in the absence of oscillations is needed for testing various oscillation hypotheses and in many other studies. It involves both measurements of the proton beam on the pulse-by-pulse basis and Monte Carlo (MC) simulations. The hadron production in the target is simulated by FLUKA2008[1] which is tuned by the data from NA61/SHINE experiment at CERN[2, 3]. The particle propagation is modeled by GEANT3[4] and GCALOR simulations[5]. The current error in the prediction of the $\nu_\mu$ flux is 11.5% at the peak energy where the uncertainty in the hadron production contributes the most, and the ratio of the predicted flux at the far and the near detectors has an uncertainty of 2%.

2.2. The Near Detector Complex

The near detector complex of the T2K experiment is located at 280 m downstream from the target and includes an Interactive Neutrino Grid detector (INGRID) situated on the nominal axis of the neutrino beam, and an off-axis detector called ND280. ND280 is a set of detectors consisting of a $\pi^0$ detector (P0D), three time projection chambers (TPCs), and two fine grained scintillator detectors (FGDs). All of them are surrounded by the calorimeters (ECal). The whole setup is confined inside a 0.2-T magnet previously used by the UA1 and the NOMAD experiments. Figure 2 shows all the components of the ND280 detector.

ND280 is used to measure un-oscillated muon neutrino flux and energy spectrum as well as contamination by the electron neutrinos, and it also provides excellent possibilities to study various neutrino cross sections. These measurements play an important role in reduction of the systematic uncertainty for the neutrino oscillation measurements described below. Neutrino CC interactions reconstructed in the ND280 FGDs and TPCs are used for this purpose. Most of the FGD material is a plastic scintillator acting as a target for neutrino interactions, and hence
they mostly occur on carbon nuclei. Most of the products of such interactions escape the FGDs and go through an adjacent TPC. A TPC is a gaseous detector filled with Ar (95%), CF$_4$ (3%) and iC$_{4}$H$_{10}$ (2%). Highly segmented MicroMEGAS[8] are used for the TPC anode and allow reconstructing tracks entering the TPC in three dimensions based on ionization charge collected by individual pads and on drift distance. The momentum of a charged particle is derived from its track curvature, whereas the particle’s type can be determined by combining information about its momentum and the deposited energy.

A CC interaction is selected by requiring to have a reconstructed $\mu^-$ which starts inside the fiducial volume of the most upstream FGD and enters the adjacent downstream TPC. There is a cut requiring no muons in the upstream TPC to reduce the out-of-fiducial-volume background. The CC interactions collected by the ND280 are sorted into 3 different categories according to the observed event topology. The first one is when there is only a negative muon exiting the interaction vertex and there are no pions or electrons observed in the same TPC or FGD. This sample mostly corresponds to CC quasi-elastic (CCQE) reaction. CC interactions where there is a positive pion in addition to the muon and no negative pions, electrons(positrons) constitutes a sample of predominantly CC resonant pion production. Finally, the third sample includes all other CC interactions and is mostly made up by deep inelastic scattering reactions.

The main contribution of the ND280 to the oscillation analyses is to constrain the neutrino flux and cross-section parameters. The prior parameters of the flux and cross sections are fitted to the data samples described above in bins of the muon angle and momentum. The detector systematic uncertainties related to the TPC and FGD track selection efficiencies and to particle identification as well as TPC momentum resolution are included. Other detector uncertainties taken into account are associated with Michel electron tagging efficiency, modeling of the pion propagation in the FGDs, outside-the-fiducial-volume events mimicking the signal and producing pile up at the time of detection. The end result of the fit is a set of constrained parameters that are propagated to the fits for the oscillation analyses in the form of vectors of point estimates and covariance matrices. The effect of the fit can be seen for those flux parameters and cross-section parameters which reflect common neutrino interactions between the near and far detectors. Figure 3 shows significant improvement in the flux normalization uncertainty at the far detector as the result of the fit. There is also a significant impact on the uncertainty in the number of electron neutrino events at the far detector. It is reduced by a factor of nine as can be seen in Figure 4.

**Figure 3.** The fitted SK $\nu_\mu$ flux normalization parameters and their error band.

**Figure 4.** Effect of the ND280 fit on the predicted number of $\nu_e$ events and background.
INGRID consists of modules of iron and scintillator plates used to measure neutrino interaction event rate at various positions orthogonal to the beam axis between $0^\circ$ and $1^\circ$. It provides the beam check in terms of the direction, intensity and stability. INGRID has been also used for a cross-section measurement published in [6].

2.3. The Super-Kamiokande Detector
The far detector of the T2K experiment is the Super-Kamiokande (SK) detector located 1000 m below the surface in the underground Kamioka Observatory on the west side of Honshu island. It is a 50-kton water Cherenkov detector with a cylindrical shape. The detector volume is separated into two parts, the inner and outer detectors. The inner detector (ID) is equipped with 11129 20-inch photomultiplying tubes (PMTs). The 22.5-kton fiducial volume is defined to be 2 m away from all the walls of the ID. The outer detector (OD) uses 1885 outward looking 8-inch PMTs and serves to reject entering background as well as to veto the events exiting the fiducial volume. The detector collects Cherenkov light produced in water by a charged particle which can be used to identify the particle and reconstruct its kinematic properties. The three dimensional view of the detector is shown in Figure 5.

The reconstruction of the neutrino events and selections for the analyses described below is done in the following way. The signal in the PMTs should be within a window of -2 to 10 $\mu$s with respect to the leading edge of a beam spill corrected for the time of flight of neutrinos and the photon propagation time from an interaction vertex to a PMT. Cherenkov light from a single particle with the energy above a threshold forms a ring pattern composed of signals in many PMTs. At the energy range of the T2K neutrinos, most of CC interactions have only an outgoing lepton above the threshold. Thus, the selection requires only one Cherenkov ring with visible energy above 30 MeV. The visible energy is defined as the energy of an electromagnetic shower that produces the observed amount of the Cherenkov light. In the case of $\nu_e$ event selection, it is required to be above 100 MeV. The reconstructed vertex should be fully contained in the fiducial volume. Low activity in the OD is also required meaning that not more than 15 neighbouring OD PMTs can have a signal in them.

Qualitatively speaking, the rings can be classified between an electron type or a muon type.
depending on their appearance. An electron ring edge is fuzzy whereas a muon ring has a sharp edge due to much less amount of multiple scattering. Also, the opening angles of the Cherenkov cone are different for the two particles. A likelihood function is constructed, and it uses the amount of charge and its arrival time in each of the PMTs to identify a type of a particle by comparing different particle hypotheses. The mis-identification probability for a muon as an electron and vice versa is less than 1%. The main background for $\nu_e$ events is the NC interaction leading to a creation of a $\pi^0$ which produces 2 gamma rays that can mimic an electron like ring. This background is reduced by 69% with the new algorithm based on the likelihood fit that takes into account time and charge probability density function for each ID PMT and has been developed based on the model from [7]. The reconstructed neutrino energy is calculated from the kinematics of the CCQE interaction on an oxygen nucleus. This energy is required to be less than 1.25 GeV for $\nu_e$ candidate events to reduce the beam intrinsic electron neutrino background significantly. For the $\nu_\mu$ sample, the reconstructed muon momentum is required to be above 200 MeV/$c$ as well as the number of decay electrons to be not greater than one. Those cuts are aimed at rejecting events with unseen muons or pions.

3. Neutrino Oscillations at T2K

As mentioned earlier, the neutrino flavour and mass eigenstates are mixed through the PMNS matrix. One can write a probability of transition from a muon to an electron neutrino as follows:

$$P(\nu_\mu \rightarrow \nu_e) \simeq \sin^2 \theta_{23} \sin^2 \theta_{13} \sin^2 \frac{\Delta m^2_{31} L}{4E} - \frac{\sin 2 \theta_{13} \sin 2 \theta_{23} \Delta m^2_{21} L}{4E} \sin^2 \theta_{13} \sin^2 \frac{\Delta m^2_{21} L}{4E} \sin^2 \delta_{CP} + \text{(CP even term, solar term, matter effect)},$$

where $L$ is the source-detector distance, and $E$ is the neutrino energy. The probability in Equation 2 is relevant to the $\nu_e$ appearance measurement. As one can see, its value is sensitive to $\sin^2 2\theta_{13}$ and $\sin \delta_{CP}$. On the other hand, the $\nu_\mu$ disappearance probability is expressed in the following form:

$$P(\nu_\mu \rightarrow \nu_\mu) \simeq 1 - 4 \cos^2 \theta_{13} \sin^2 \theta_{23} (1 - \cos^2 \theta_{13} \sin^2 \theta_{23}) \sin^2 \frac{1.267 \Delta m^2 L}{E},$$

and so the disappearance measurement is sensitive to $\sin^2 2\theta_{23}$ and the absolute value of the $\Delta m^2$ which is either $\Delta m^2_{32}$ or $\Delta m^2_{13}$ for normal or inverted hierarchies respectively. One can also notice that the appearance and disappearance measurements in the three-flavour framework depend on each other via $\theta_{13}$ and $\theta_{23}$ angles. Historically, the $\nu_e$ appearance analysis [9] has been done with a fit for $\theta_{13}$ whereas the other oscillation parameters were kept fixed. The $\nu_\mu$ disappearance study [10] fits for $\theta_{23}$ and $\Delta m^2$ keeping the other parameters constrained at their best known values within errors. In addition to those studies, this review presents the results from the joint analysis [11] done to properly take the forementioned interdependence into account.

3.1. Observation of Electron Neutrino Appearance

The detailed results of the $\nu_e$ appearance observation are given in [9]. After all the cuts, there were 28 electron neutrino events selected in the SK sample whereas $4.92 \pm 0.55$ are expected from the background in the case of no oscillation, if $\theta_{13} = 0$. The values for the $\theta_{13}$ angle in the case of both normal and inverted hierarchies were obtained using a binned maximum likelihood fit in bins of the outgoing lepton momentum and angle. The likelihood is constructed from four
The likelihood is marginalized over experiments as an average given in [12] and its associated error. It is illustrated in Figure 6. described above was also performed using a constrained value of $\theta$ to $\delta$ no oscillation assumption.

The fit for the $\theta_{13}$ angle was done using the following values of the other oscillation parameters: $\sin^2 \theta_{12} = 0.306$, $\Delta m^2_{21} = 7.6 \times 10^{-5} \text{ eV}^2$, $\sin^2 \theta_{23} = 0.5$, $|\Delta m^2_{32}| = 2.4 \times 10^{-3} \text{ eV}^2$ and $\delta_{CP} = 0$. For the normal (inverted) hierarchies the fitted value is $\sin^2 2\theta_{13} = 0.140^{+0.038}_{-0.032}$ ($0.170^{+0.045}_{-0.037}$) with the 68% confidence levels (C.L.). The significance of this result is 7.3$\sigma$ that was calculated in two different ways: using the difference in likelihoods between the best fit and the case of no oscillation, or alternatively comparing with a large number of toy simulations generated under no oscillation assumption.

As shown in the Equation 2 above, the electron neutrino appearance measurement is sensitive to $\delta_{CP}$. In order to check possible constraints on its value given the observed data, the fit described above was also performed using a constrained value of $\theta_{13}$ taken from the reactor experiments as an average given in [12] and its associated error. It is illustrated in Figure 6. The likelihood is marginalized over $\sin^2 2\theta_{13}$, $\sin^2 \theta_{23}$ and $\Delta m^2_{32}$. The preferred value of $\delta_{CP}$ is $-\pi/2$, and regions between 0.19$\pi$ and 0.80$\pi$ for NH (between $-\pi$ and $-0.97\pi$, and $-0.04\pi$ and $\pi$ for IH) are excluded at 90% C.L.

3.2. Precise Measurement of the $\theta_{23}$ from Neutrino Disappearance

The results of this study are presented in [10]. There are 120 $\nu_\mu$ events selected after the cuts described in Section 2.3 above. In the case of no oscillation, the simulation predicts 446 $\pm$ 22.5 events. An un-binned maximum likelihood fit is used to obtain the values for $\sin^2 \theta_{23}$ and $\Delta m^2_{32}$ for NH ($\Delta m^2_{43}$ for IH). There are 45 systematic parameters included in the fit: 11 cross-section parameters related to neutrino interactions exclusively in the ND280 detector, 23 beam flux and cross-section parameters which are common for neutrino interactions at the ND280 and the SK, 7 systematic parameters related to pion interactions at the SK detector, and finally the oscillation parameters $\sin^2 \theta_{13}$, $\sin^2 \theta_{12}$, $\Delta m^2_{21}$ and $\delta_{CP}$. $\delta_{CP}$ is unconstrained, whereas $\sin^2 \theta_{13}$ = 0.0251$^{+0.0035}_{-0.0035}$, $\sin^2 \theta_{12}$ = 0.312$^{+0.016}_{-0.016}$, $\Delta m^2_{21} = (7.50 \pm 0.20) \times 10^{-5} \text{ eV}^2/\text{c}^4$ are fit with constraints from PDG values found in [13]. Figure 7 shows the best fit value for $\sin^2 \theta_{23}$ and $\Delta m^2_{32}$. As one can see, the results are compatible with the other experiments. The results of the fit with one-dimensional 68% confidence intervals are $\sin^2 \theta_{23} = 0.514^{+0.055}_{-0.055}$ and $\Delta m^2_{32} = (2.51$
$\pm 0.10 \times 10^{-3} \text{eV}^2/c^4$ for the normal hierarchy, and $\sin^2 \theta_{23} = 0.511 \pm 0.055$ and $\Delta m^2_{13} = (2.48 \pm 0.10) \times 10^{-3} \text{eV}^2/c^4$ for the inverted hierarchy. The confidence intervals are estimated for a parameter of interest by marginalizing over the other parameter.

### 3.3. Joint Analysis of the $\nu_e$ and $\nu_\mu$ Samples

As we saw from the Equations 2 and 3, the oscillation parameters are correlated between the $\nu_e$ appearance and $\nu_\mu$ disappearance studies and so a simultaneous fit of the both samples is preferred. Two independent fits have been performed. One is based on a frequentist approach and the second one is Bayesian. They give similar results and act as a crosscheck to each other. Here, the oscillation parameters $\Delta m^2$, $\sin^2 \theta_{13}$, $\sin^2 \theta_{23}$ and $\delta_{CP}$ are obtained simultaneously. A binned likelihood function is used to minimize the difference between the observed and predicted number of both CC $\nu_e$ and $\nu_\mu$ events in bins of reconstructed energy. In the case of the frequentist approach, the flux and cross-section uncertainties are taken into account in the same way as in the standalone analyses with the ND280 fit performed. The analysis was preformed with and without a constraint on the $\theta_{13}$ from the reactor experiments.

The results of the fit without the reactor constraint are the following for the cases of NH (IH): $\sin^2 \theta_{23} = 0.524_{-0.059}^{+0.057} (0.523_{-0.065}^{+0.055})$, $\sin^2 \theta_{13} = 0.042_{-0.021}^{+0.013} (0.049_{-0.021}^{+0.015})$, and $\Delta m^2_{32} = 2.51_{-0.12}^{+0.11} \times 10^{-3} \text{eV}^2/c^4$ ($\Delta m^2_{13} = 2.49_{-0.12}^{+0.10} \times 10^{-3} \text{eV}^2/c^4$). The fit results with the reactor constraint included provide some constraints on the value of $\delta_{CP}$ similar to the results described in section 3.1. In Figure 8 one can see that the excluded regions at 90%CL for the $\delta_{CP}$ are $[0.15, 0.83]\pi$ for NH, and $[-0.08, 1.09]\pi$ for IH.

The Bayesian approach is based on combining prior information about the systematic parameters and external experimental data with a likelihood function in order to calculate a posterior probability of a hypothesis when given the observed data. A numerical integration technique called Markov Chain Monte Carlo is used to achieve this goal. As opposed to the frequentist approach, this analysis simultaneously fit the three ND280 CC $\nu_\mu$ interaction samples described in section 2.2 as well as the $\nu_e$ and $\nu_\mu$ samples from SK. The analysis shows similar results as the frequentist approach. Figure 9 shows the posterior probability for $\delta_{CP}$ when the reactor constraint is taken into account. As one can be see, the values close to $-\pi/2$ are preferred. In both frequentist and Bayesian approaches, normal hierarchy has a slight preference but inverted hierarchy is not excluded at any significant level. The details of both studies are presented in [11].
3.4. Search for Sterile Neutrinos

Another oscillation study by T2K is a search for $\nu_e$ disappearance or search for sterile neutrinos. As opposed to the measurements at SK with a long baseline this study exploits possible oscillation at a short baseline of 280 m between the target and the ND280 detector. There is some experimental evidence in the MeV energy range, suggesting electron neutrino deficit over short propagation baselines from intense radioactive sources [16, 17, 18] and electron antineutrino deficit from nuclear reactors [19]. These discrepancies could be explained by a model with neutrinos oscillating into a sterile state(s). Using a two-mass state approximation the survival probability for $\nu_e$ can be written as:

$$P_{\nu_e}^{(\nu_e) \rightarrow (\bar{\nu}_e)} = 1 - \sin^2 2\theta_{ee} \sin^2 \left( 1.267 \frac{\Delta m_{eff}^2 L}{E} \right),$$  

where there are two parameters of interest: $\Delta m_{eff}^2 [eV^2/c^4]$, the mass squared difference between a hypothesized sterile mass state and the weighted average of the standard three mass states, and also the oscillation angle in the amplitude term $\sin^2 2\theta_{ee}$. The energy is expressed in MeV and the baseline length is in meters.

A sample of CC $\nu_e$ interactions collected by the ND280 detector is used to perform a likelihood ratio fit to the reconstructed energy spectrum of neutrinos. Electron neutrinos are produced at the T2K beamline mainly from the decays of charged and neutral kaons at energies above 1 GeV and at lower energies from the muon in-flight decays. Due to different life times of the parent particles there is a spread of propagation distances of electron neutrinos detected at ND280. The averaged neutrino flight path for the events selected in this analysis is 244 m. The neutrino flux is modeled in the same way as described in section 2.2. Also, the fact that $\nu_\mu$ and $\nu_e$ are produced to a large extent in the same decays allows using the sample of CC $\nu_\mu$ interactions at ND280 to constrain the prediction for the $\nu_e$ flux in this analysis. The main background for the electron neutrino sample comes from deep inelastic or NC interactions producing neutral pions which decay and lead to gamma-to-electron conversion. The pion background is reduced by rejecting events with positron-like tracks near the interaction point and requiring the invariant mass to be less than 100 MeV/c^2. Also, a high purity sample of $\nu_\mu N \rightarrow \pi^0 X$ interactions is used to control the background.
The oscillation parameters are obtained from a Poisson binned likelihood with a simultaneous fit of the $\nu_e$ and control samples in bins of the reconstructed energy. The best fit oscillation parameters are $\sin^2 2\theta_{ee} = 1$ and $\Delta m^2_{\text{eff}} = 2.05 \text{ eV}^2/c^4$. Figure 10 shows two-dimensional contours computed with Feldman-Cousins method [23]. At a 95% C.L., the region of $\sin^2 2\theta_{ee} > 0.3$ and $\Delta m^2_{\text{eff}} > 7 \text{ eV}^2/c^4$ is excluded. The exclusion region lies within the region excluded by the combination of solar[21] and KamLAND[22] data. The p-value of the null oscillation hypothesis is 8.5%.

4. Selected Cross-section Results from T2K

Uncertainties in cross-section measurements play a negative and relatively large role in the oscillation analyses above in the range of neutrino energies of T2K. Besides doing studies related to the neutrino oscillation phenomena, T2K aims at measuring different neutrino cross sections for the purpose of improving neutrino interactions models and obtaining more precise oscillation results. For example, future measurements of possible CP violation in the lepton sector will need a precise knowledge of both $\nu_\mu$ and $\nu_e$ interactions. The ND280 near detector is particularly suited for a variety of cross-section measurements, and some can be also done at SK. The measurement of inclusive muon neutrino cross section has been reported in [24]. Two selected cross-section results from T2K are presented below.

4.1. Charged Current Inclusive Electron Neutrino Cross Section

The differential CC $\nu_e$ inclusive cross section has been measured by T2K for the first time as well as the flux averaged total cross section. It is measured in bins of the outgoing electron momentum and angle, and four-momentum transfer, $Q^2$, of the interaction. This result is based on $5.9 \times 10^{20}$ POT. The TPC ionization measurement along with possible presence of an electromagnetic shower in the ECAL allow for effective selection of electron-like events. The gamma-to-electron conversion is an important background which is checked and reduced as described in Section 3.4 above. 315 CC $\nu_e$ interaction candidates are used in the analysis.

The flux averaged differential cross section for variable $X$ in a given bin $t_k$, can be written as:

$$\left\langle \frac{\partial \sigma(\phi)}{\partial X} \right\rangle_{t_k} = \frac{N_{t_k}}{\Delta X_{t_k} T_{\phi}},$$

where $X$ represents the electron angle, momentum or $Q^2$, $N_{t_k}$ is the total number of events in a true bin of width $\Delta X$, $T = 5.5 \times 10^{20}$ is the number of target nucleons (in the fiducial
Figure 11. Total $\nu_e$ CC inclusive cross section when unfolding through $Q^2_{CC}$. The T2K data point corresponds to the $\nu_e$ mean flux. The vertical error represents the total uncertainty and the horizontal error bar represents 68% of the flux on either side of the mean. The T2K flux prediction is shown in gray. The NEUT and GENIE predictions are the total $\nu_e$ CC inclusive predictions as a function of neutrino energy. The NEUT and GENIE averages are the flux-averaged predictions. The Gargamelle $\nu_e$ and T2K $\nu_\mu$ cross-section results are also shown.

volume of the upstream FGD), $\phi = 1.35 \times 10^{11}$ cm$^{-2}$ is the total integrated flux. The event numbers used in Eq. 5 are the numbers inferred from the reconstructed event numbers in reconstructed bins using an unfolding technique described in [26]. The reconstructed $Q^2$ is calculated assuming CCQE kinematics. The total flux averaged cross section is given by the sum over all the bins: $\langle \sigma \rangle \phi = \sum_{k=1}^{n_t} N_{tk}/T\phi$, and it is calculated to be $1.11 \pm 0.21 \times 10^{-38}$ cm$^2$/nucleon. Figure 11 shows the result in comparison with neutrino generators and other experimental data. The differential cross sections in bins of the electron momentum, angle and $Q^2$ have been also calculated and can be found in [25]. There is a good agreement between these results and the predictions from both NEUT[27] and GENIE[28] neutrino generators.

4.2. Neutrino-oxygen Neutral Current Cross Section Measured at Super-Kamiokande

The NCQE interaction on oxygen is dominant among the other neutral current processes at neutrino energies of $\sim 500$ MeV. It can be expressed as $\nu + ^{16}\text{O} \rightarrow \nu + p + ^{15}\text{N}^*$ (or $\nu + n + ^{15}\text{O}^*$) where the excited nucleus in the final state de-excites via gamma ray emission. It is also possible for the knocked out nucleon to interact with other nuclei in water producing gamma rays as well. Both sources of gamma rays are the biggest background for the detection of astrophysical neutrinos at 10 MeV energy scale. Super-Kamiokande detector allows measuring the cross section for this process.

The total statistics used in this analysis is based on $3.01 \times 10^{20}$ POT. The event selection is based on the signal timing in the ID PMTs. The signal has to be within 200 ns window in at least 25 PMTs and be inside the T2K beam time window of 1 ms. The reconstruction of event vertex, direction and energy is the same as of SK solar neutrino analysis [31]. The reconstructed event direction and energy are determined using a MC simulation of mono-energetic electrons, and the vertex position is found by fitting the timing residual of the collected light. The vertex position is resolved in the range from 0.5 to 1.25 m for the energies of gamma rays between 12 and 4 MeV. For event simulation a multistage MC is used starting from the neutrino flux simulation described in Section 2.1 which is then used by the NEUT generator to simulate the neutrino interactions at SK. The particles produced in an interaction and the PMT response are simulated using GEANT3, GCALOR and custom made routine based on NEUT.

After all the cuts there are $N_{\text{obs}} = 43$ observed events in the 4-30 MeV range of interest,
Figure 12. The expected $\Delta \chi^2$ for the $\sin \delta_{CP} = 0$ hypothesis, plotted as a function of true values of $\delta_{CP}$ for various values of $\sin^2 \theta_{23}$ in the case of normal hierarchy and 100% operation in the neutrino mode production. The systematic errors are taken from the T2K 2012 oscillation analyses [34, 35].

Figure 13. The expected $\Delta \chi^2$ for the $\sin \delta_{CP} = 0$ hypothesis, plotted as a function of true values of $\delta_{CP}$ for various values of $\sin^2 \theta_{23}$ in the case of normal hierarchy and operation mode with 50% neutrino and 50% anti-neutrino production. The systematic errors are taken from the T2K 2012 oscillation analyses [34, 35].

and $N^{\text{exp}} = 51.0$ are expected from the simulation whereas the number of expected background events is $N^{\text{bkg}} = 16.2$. Most of the background events originate from NC non-QE interactions. The event vertex positions are uniformly distributed within the fiducial volume. The data show a 6 MeV peak from the primary ray de-excitation. The total systematic error for the NCQE signal is 23% and 25% (31%) for the non-QE NC (CC) reactions. The NCQE cross-section measurement is scaled based on the theoretical prediction from [29], and is expressed as $\langle \sigma_{\nu,\text{NCQE}}^{\text{obs}} \rangle = (N^{\text{obs}} - N^{\text{bkg}}) / (N^{\text{exp}} - N^{\text{bkg}}) \langle \sigma_{\nu,\text{NCQE}}^{\text{theory}} \rangle$, where $\langle \sigma_{\nu,\text{NCQE}}^{\text{theory}} \rangle = 2.01 \times 10^{-38}$ cm$^2$. The resulting cross-section is $1.55 \times 10^{-38}$ cm$^2$ at the median neutrino flux energy of 630 MeV with the 68% confidence interval of $(1.20, 2.26) \times 10^{-38}$ cm$^2$ including statistical and systematical uncertainties. The measurement is consistent with the theory at 68% C.L. Further details of the study can be found in [30].

5. Future of T2K

After achieving the initial goal of observing the oscillation of $\nu_\mu$ to $\nu_e$, the T2K experiment has many exciting goals to reach in both short and long terms. These include precision measurements (at 1% level) of the $\sin^2 2\theta_{23}$ in order to determine which octant the $\theta_{23}$ angle lies in, and also, a precise determination of $\Delta m^2_{32}/(\Delta m^2_{13})$ at $10^{-4}$ eV$^2$ level. Given the ability of T2K to switch between a muon neutrino or muon anti-neutrino beam, the search for electron anti-neutrino appearance is performed and will be reported soon. By the end of 2014, T2K has collected $1.808 \times 10^{20}$ POT in the anti-neutrino mode. The fact that the value of $\theta_{13}$ is large opens a way to future measurements of CP violation in the lepton sector. A study was made to estimate capabilities of the T2K experiment in this respect based on the full projected POT. The summary is presented in the next two sections.
5.1. T2K Future Sensitivity to Oscillation Parameters

The full statistics of $7.8 \times 10^{21}$ POT is expected in both neutrino and anti-neutrino mode. An estimate of T2K sensitivity to various oscillation parameters is made with statistical errors only, with the systematic errors as of 2012 or errors projected for the fully collected statistics. The sensitivity is calculated to $\sin^2 2\theta_{13}$, $\delta_{CP}$, $\sin^2 2\theta_{23}$ and $\Delta m^2_{32}$, and it depends on the true value of the parameters. The sensitivity study utilizes the three-flavour neutrino mixing model. A number of combined likelihood fits is done to the reconstructed energy spectra of both $\nu_e$ and $\nu_\mu$ simultaneously, and for the anti-neutrino mode as well. The reconstructed observable spectra are generated for each test point, $\theta$, in the space of oscillation parameters. A hypothesis is constructed for the parameters of interest and it is tested using a $\Delta \chi^2$-type of test defined as $\Delta \chi^2 = \chi^2(H_0) - \chi^2_{\text{min}}$, where $\chi^2(H_0) = -2 \ln \mathcal{L}(\theta|H_0)$, and $\mathcal{L}(\theta|H_0)$ is the likelihood of observing the spectrum generated with $\theta$ when the “true” values are given by $H_0$. For each study, the tested parameters are fixed whereas the other oscillation parameters are fit to minimize $\chi^2(H_0)$.

The full study is presented in [32]. Here, the results concerning sensitivity to $\delta_{CP}$ are presented. Looking at Figures 12 and 13, one can compare $\Delta \chi^2$ plotted as a function of true values of $\delta_{CP}$ for normal hierarchy in the case if the collected data are neutrino only and in the case of half-neutrino and half-anti-neutrino mode of operation. A significant improvement in the sensitivity can be seen for the latter case. For some ranges of the $\delta_{CP}$ values T2K data in the future will provide sensitivity at more than 90% C.L. as shown in Figure 13. T2K will also have an ability to reject maximal mixing of $\theta_{23}$ or reject its octant. In general, it has been shown that collecting an equal amount of data in neutrino and anti-neutrino modes gives the best results in terms of the sensitivity.

5.2. T2K in Combination with NOνA

The NOνA experiment, which has recently started collecting data, has sensitivities to the oscillation parameters similar to T2K and better sensitivity to the mass hierarchy due to the longer baseline and hence enhanced matter effects. Figure 14 shows that T2K ability to measure the value of $\delta_{CP}$ is greatly enhanced by combining with NOνA. As one can see, the range of $\delta_{CP}$ values is extended significantly. Also, combination of NOνA and T2K data allows for an improved measurement of the mass hierarchy as shown in Figure 15. The GLoBES analysis package [33] which works similar to the method described above in Section 5.1 is used. A reasonable normalization uncertainties of 5% for the signal and 10% for the background were used for both experiments. Further details including sensitivity plots for other cases (inverted hierarchy, running in 100% neutrino mode etc) and oscillation parameters can be found in [32].

6. Summary

With 8.4% of the total approved POT T2K experiment has achieved such significant results as discovery of the transition between a muon and an electron neutrinos with $7.3\sigma$ significance, and also has measured the associated $\theta_{13}$ angle. Combining T2K and reactor measurements allowed constraining $\delta_{CP}$ value at 90% C.L. The muon neutrino disappearance study has shown nearly maximal atmospheric mixing. Also, T2K has a diverse cross-section measurement program aimed at improving oscillation analyses and neutrino interaction models.

In the future, given more statistics and constantly improving analyses, T2K will make a precise measurement of $\theta_{23}$ to determine its octant and of $\Delta m^2_{32}$ at the level of $10^{-4}$ eV$^2$. In combination with NOνA or other experiments, which are sensitive to the mass hierarchy, T2K is capable of measuring $\delta_{CP}$ and contributing to the mass hierarchy puzzle over a significant range of oscillation parameters.

References
Figure 14. The expected $\Delta \chi^2$ for the sin $\delta_{CP} = 0$ hypothesis, plotted as a function of true values of $\delta_{CP}$ for various values of $\sin^2 \theta_{23}$ in the case of normal hierarchy assumed to be true. Dashed (solid) curves indicate studies where normalization systematic uncertainties are (not) considered. Combined prediction for T2K and NOvA assuming T2K running in 50% neutrino and 50% anti-neutrino mode.

Figure 15. The expected $\Delta \chi^2$ for rejecting the incorrect mass hierarchy hypothesis, plotted as a function of true values of $\delta_{CP}$ in the case of normal hierarchy assumed to be true. Dashed (solid) curves indicate studies where normalization systematic uncertainties are (not) considered. Combined prediction for T2K and NOvA assuming T2K running in 50% neutrino and 50% anti-neutrino mode.

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