

First Oscillation Results for the T2K Experiment

M. Hartz, for the T2K Collaboration
*Department of Physics, University of Toronto, 60 St. George St.,
Toronto, M4V 2B8, Canada*

T2K is a long baseline high intensity neutrino oscillation experiment employing an off-axis design to search for the as yet unobserved appearance of ν_e neutrinos in a ν_μ beam. The neutrino beam originates at the J-PARC facility in Tokai, Japan and the Super-Kamiokande (SK) detector, located 295 km away, measures the composition of the oscillated beam. The SK data are searched for an excess of ν_e , constraining the allowed parameter space of $\sin^2(2\theta_{13})$, the parameter governing the amplitude of oscillations from ν_μ to ν_e . This amplitude is of particular interest since it also modulates the amplitude of CP violating terms in the lepton mixing matrix. This paper presents results from the first T2K physics run in 2010 with 3.23×10^{19} protons on target.

1 Introduction

In the three flavor oscillation model, neutrino mixing is parameterized by three mixing angles, θ_{12} , θ_{23} and θ_{13} and a CP violating phase δ_{CP} . Additionally the oscillation probabilities depend on the mass squared differences between the neutrino mass eigenstates, Δm_{12}^2 and Δm_{23}^2 . The mixing through θ_{12} has been well constrained by solar¹ and reactor² experiments, while mixing through θ_{23} has been constrained by atmospheric³ and accelerator based^{4 5} experiments. Searches for oscillations depending on θ_{13} have so far been inconclusive, but measurements by the CHOOZ⁶ and MINOS⁷ experiments place upper limits on its value, $\sin^2(\theta_{13}) < 0.12 - 0.15$ at 90% C.L..

The T2K (Tokai to Kamioka) experiment is a long baseline experiment designed with the primary goal of searching for the appearance of electron neutrinos in a muon neutrino beam to measure the mixing angle θ_{13} . To leading order, the oscillation probability is:

$$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2(\theta_{23})\sin^2(2\theta_{13})\sin^2\left(\frac{\Delta m_{23}^2 L}{4E_\nu}\right) \quad (1)$$

If the mixing angle θ_{13} is found to be non-zero, then the observation of CP violation in neutrino mixing will be possible, and T2K will play an important role in searching for it. This paper describes the first search for ν_e appearance at T2K.

2 The T2K experiment

The T2K experiment is described in detail elsewhere.⁸ A brief description of the experiment follows. The T2K muon neutrino beam is produced when 30 GeV protons from the J-PARC accelerator facility collide with a 90 cm graphite target. Positively charged particles (predominantly pions) produced in the collisions are focused by three magnetic horns and allowed to

decay in a 96 m long decay volume. The decay of the π^+ hadrons produces a beam of ν_μ . Decays of muons and kaons contaminate the beam with ν_e at the level of 1%.

T2K employs two near detectors located 280 m from the graphite target to measure the properties of the un-oscillated beam, and a far detector, the Super-Kamiokande (SK) detector, located 295 km away to measure the oscillated beam. SK sits 2.5° from the axis of the neutrino beam. This off-axis angle takes advantage of the decay kinematics of pions to produce a narrow band beam at the off-axis detector that peaks at the energy where neutrino oscillations are expected.⁹

The INGRID near detector consists of 16 modules, 14 of which are arranged in a cross configuration, centered on the beam axis. These modules consist of iron and scintillator layers and measure the neutrino rate and profile on the beam axis direction. The ND280 off-axis near detector is located off the beam axis in the same direction as SK and is used to measure the properties of the un-oscillated off-axis beam. ND280 consists of a number of sub-detectors, but for the analysis presented here, the Fine Grained Detectors (FGDs) and Time Projection Chambers (TPCs) are used. The two FGDs consist of scintillator bars, with the second also including water targets. Their 2.2 tons of mass provide the target material for neutrino interactions, and the scintillation light is read out to reconstruct particle tracks near the interaction vertices. The three TPCs measure the momentum of charged particles in ND280's 0.2 T magnetic field to better than 10% at 1 GeV/c. They also provide dE/dx measurements with $< 10\%$ resolution for particle identification.

The SK detector is a 50 kton water Cherenkov detector that consists of an inner (ID) and outer (OD) detector. The OD is used to veto events that enter or exit the ID. Neutrino interactions taking place in the 22.5 kton fiducial volume of the ID are detected by the Cherenkov light from charged interaction products produced above threshold. Photo-multiplier tubes instrumenting the walls of the ID image the Cherenkov light rings and the properties of the rings are used to reconstruct the particle type, energy and vertex position.

The primary neutrino interaction mode that is of interest for T2K is the charged-current quasi-elastic (CCQE) interaction, where a charged lepton and recoil nucleons are the only final state particles. This interaction mode is significant at T2K energies and allows for the approximate reconstruction of the neutrino energy if the charged lepton kinematics and neutrino beam direction are known. An important background interaction mode for T2K is the neutral-current π^0 (NC π^0) mode. Here the final state includes the undetected neutrino, a π^0 and recoil nucleons. The π^0 decays to two photons that can be misidentified as a single electron in the SK detector.

The measurement described in this paper uses data accumulated with 3.23×10^{19} protons on target from January through June of 2010.

3 Electron neutrino appearance analysis

To measure θ_{13} , T2K searches for an excess of ν_e candidate events observed at SK that can be interpreted as $\nu_\mu \rightarrow \nu_e$ oscillations. There are two major sources of background ν_e candidates at SK that must be accounted for: intrinsic ν_e contamination of the beam from muon and kaon decays and non ν_e interactions that are reconstructed as ν_e , in large part consisting of NC π^0 interactions. The background and oscillation signal predictions are produced using model and data based simulations of the neutrino flux and interactions, as well as the constraint from an inclusive ν_μ measurement made using the ND280 detector. The data over simulation rate measured at ND280 is used to renormalise the SK prediction:

$$N_{SK}^{exp} = N_{ND280}^{data} / N_{ND280}^{MC} \times N_{SK}^{MC} \quad (2)$$

By doing this, the neutrino rate prediction is constrained by the near detector data, and significant cancellations in the neutrino flux uncertainties are realized. The SK ν_e selection is applied

to the simulation as well as the data, and the measured number of events compared to the prediction provides a constraint on θ_{13} .

3.1 SK ν_e selection

The selection criteria for ν_e candidates at SK was finalized before looking at the data to avoid bias. Cuts were optimized for the relatively small expected sample size of T2K’s initial data sets. The selection looks for events with a single electron like ring that will be produced by the final state electron in CCQE interaction of ν_e .

The selection of SK ν_e candidates begins with the sample of neutrino interaction candidates that are fully contained in the ID with vertices in the fiducial volume. A > 100 MeV visible energy cut is applied to reduce the backgrounds from neutral current interactions or electrons from muon decays. The candidates are required to have a single ring, and the ring must be identified as an electron like ring. Electron rings are identified by their “fuzzy” edges compared to muon rings due to the electromagnetic scattering of the electron in the water. No delayed activity can be observed in the detector as this is interpreted as electrons from muon decays. For each event, a π^0 mass is reconstructed under the two ring hypothesis, and if $m_{\pi^0} > 105$ MeV/ c^2 the event is rejected. This cut removes background due to photons from π^0 decays. Finally, the reconstructed energy of the ν_e candidate is required to be < 1250 MeV since the oscillation probability peaks below 1000 MeV. This selection has an efficiency of 66% for signal events with efficiency uncertainties of 7.6% and 15.8% for signal and background respectively.

3.2 Flux prediction

The flux prediction is made from the simulation of protons interacting in the T2K target and the subsequent propagation of secondary particles through the magnetic horns and decay volume until they decay to produce neutrinos. T2K proton beam monitor measurements are used to set the initial conditions for the protons in the simulation. The production of pions by proton interactions inside the target are modeled with data from the NA61 experiment¹⁰, while other in-target interactions are modeled with FLUKA.^{11 12} Propagation of particles outside the target is carried out with GEANT3¹³ and hadron interactions are modeled with the GCALOR¹⁴ package. Fig. 1 shows the expected ν_μ and ν_e neutrino fluxes seen by SK, broken down by the parent particle that produces the neutrino. The ν_μ produced in the < 1 GeV region of interest are predominantly from pion decays, while the ν_e contamination is predominantly from muon decays. The dominant sources of uncertainty in the neutrino flux come from the production of pions and kaons in the interactions of protons, and the total flux uncertainty contributes a 9.2% uncertainty to ν_e background candidate prediction.

3.3 Neutrino interaction modeling

The interactions of neutrinos are modeled with the NEUT¹⁵ neutrino interaction generator, while the GENIE¹⁶ neutrino interaction generator is used for cross-checks. The uncertainties on the neutrino interaction models are evaluated in three ways:

- Comparisons between models
- Variations of parameters within models
- Comparisons to data from the MiniBooNE¹⁷ and SciBooNE^{18 19} experiments, as well as the SK atmospheric data set

The uncertainty on the SK ν_e candidate sample size from background sources due to neutrino interaction uncertainties is 14.2%. The dominant sources of uncertainties are final state interactions of pions, and the NC π^0 cross section.

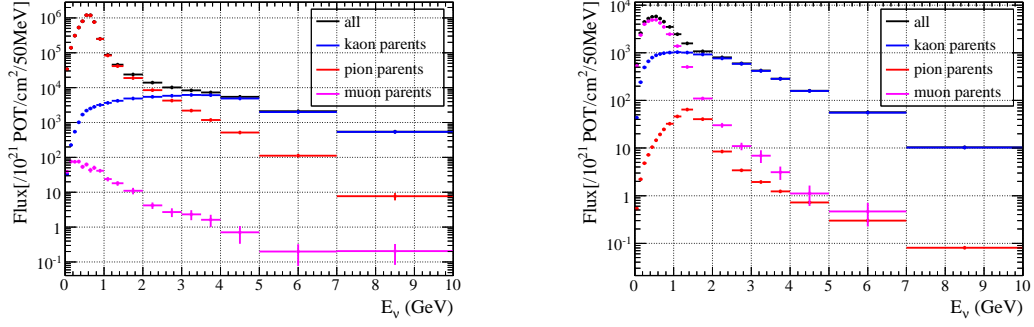


Figure 1: Predicted ν_μ (left) and ν_e (right) fluxes at SK based on simulation. Error bars represent the statistical uncertainty of the simulated flux.

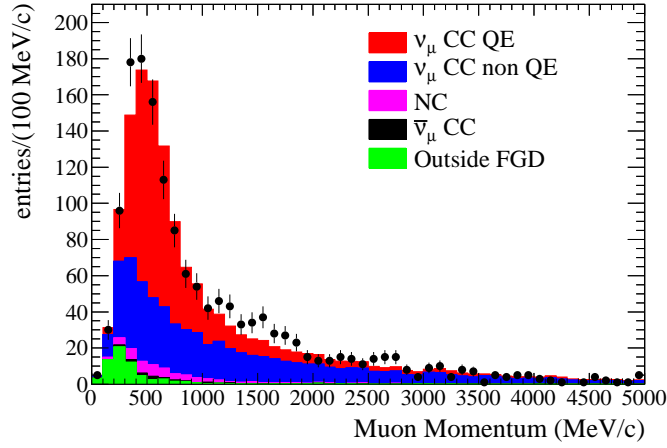


Figure 2: Muon momentum from the inclusive ν_μ interaction data measured at ND280. Error bars represent the statistical uncertainty of the data points.

3.4 ND280 inclusive ν_μ measurement

The rate of ν_μ charged current interactions is measured by ND280 using a sample of events where a negative track originates in one of the two FGDs and is tracked by the downstream TPC. The TPC dE/dx measurement is used to select muons and reject electrons, resulting in a sample that is 90% ν_μ charged current interactions, and 50% CCQE. Fig. 2 shows the predicted distribution of reconstructed muon momentum compared to the measured distribution. The ratio of data over the prediction for the full sample is:

$$N_{ND280}^{data}/N_{ND280}^{MC} = 1.061 \pm 0.028(stat.)_{-0.038}^{+0.044}(syst.) \pm 0.039(phys.model) \quad (3)$$

This ratio is used to renormalise the SK event rate predictions, and the uncertainties on this ratio are propagated into uncertainty on the predicted SK samples.

3.5 SK ν_e prediction

Using the flux prediction, neutrino interaction models and near detector measurement, the background and signal expectations for ν_e candidates at SK are calculated. Table 3.5 shows the predictions for 3.23×10^{19} p.o.t. and $\sin^2(2\theta_{13}) = 0.1$. The background prediction is

Table 1: SK ν_e candidate predictions for 3.23×10^{19} p.o.t. and $\sin^2(2\theta_{13}) = 0.1$.

Source	Events	Systematic Error
Background	0.30	23.9%
Beam ν_e (85% CCQE)	0.16	
ν_μ (95% NC)	0.13	
$\bar{\nu}_\mu$	0.01	
Signal ν_e	1.20	19.5%

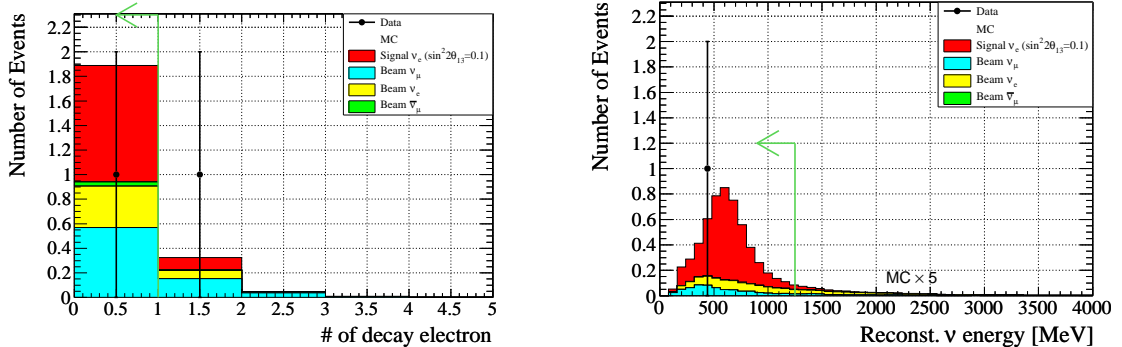


Figure 3: Data and predicted ν_e candidate samples at the decay electron (left) and reconstructed neutrino energy (right) cuts.

$0.30 \pm 0.07(\text{syst.})$ events. The dominant sources of uncertainty come from the flux prediction, neutrino interaction modeling and SK ring counting, particle ID and π^0 mass cuts.

3.6 SK data sample and interpretation

The ν_e selection cuts are applied to the SK data and the resulting number of events is used to place a constraint on θ_{13} . Fig. 3 shows the effect of the decay electron and reconstructed neutrino energy cuts on the data and predicted distributions. After all cuts are applied, one candidate event remains. With this single event and the background and signal predictions, limits on $\sin^2(2\theta_{13})$ are calculated using the Feldman-Cousins²⁰ method. The resulting 90% C.L. limit for varying δ_{CP} are shown in Fig. 4. For $\delta_{CP} = 0$, $\Delta m_{23}^2 = 2.4 \times 10^{-3} \text{ eV}^2$ and $\sin^2(2\theta_{23}) = 1.0$ the 90% C.L. upper limit is found to be 0.5.

4 Conclusion

T2K has carried out a search for ν_e appearance in a ν_μ beam with data produced from 3.23×10^{19} protons on target. In these data, T2K observes one ν_e candidate event at the SK detector when $0.30 \pm 0.07(\text{syst.})$ events are expected from background sources. T2K sets the upper limit $\sin^2(2\theta_{13}) < 0.5$ at 90% C.L. (for $\Delta m_{23}^2 = 2.4 \times 10^{-3} \text{ eV}^2$ and $\sin^2(2\theta_{23}) = 1.0$). Although this first measurement from T2K does not yet challenge the sensitivity of previous experiments' measurements, future T2K measurements will follow, with four times the data set already available, promising interesting results in the near future.

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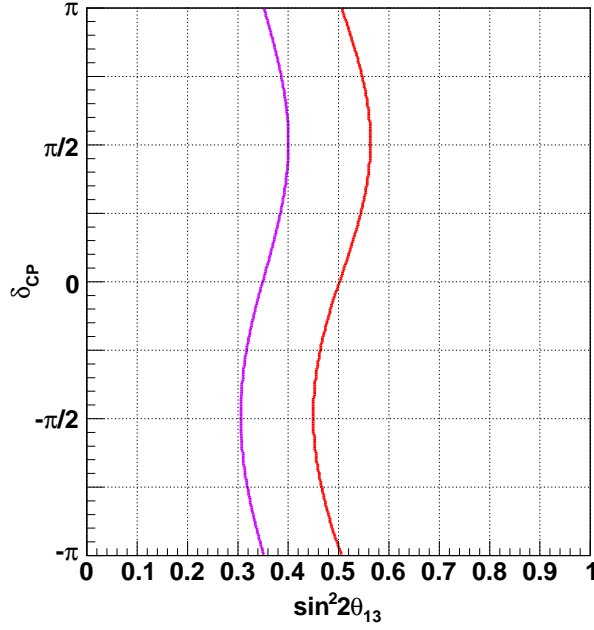


Figure 4: The 90% C.L. upper limit (red) and sensitivity (magenta) for the T2K data set with $\Delta m_{23}^2(> 0) = 2.4 \times 10^{-3} eV^2$ and $\sin^2(2\theta_{23}) = 1.0$.

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