Results from T2K

Martin David Haigh, University of Warwick

On behalf of the T2K Collaboration.

To appear in the proceedings of the Interplay between Particle and Astroparticle Physics workshop, 18 – 22 August, 2014, held at Queen Mary University of London, UK.

1 Introduction

The Tokai to Kamioka (T2K) experiment uses a beam of muon neutrinos, produced at the J-PARC facility on the east coast of Japan, to study neutrino oscillations driven by the $\Delta m_{\text{atm}}^2$ mass splitting. A suite of near detectors located 280 m from the secondary beam source samples the unoscillated beam, and the Super-Kamiokande water Cherenkov detector samples the beam at a baseline of 295 km, and at a point 2.5$^\circ$ off the beam axis, giving a narrow-band beam centred around 600 MeV. Analyses of the oscillation channels $\nu_\mu \rightarrow \nu_e$ and $\nu_\mu \rightarrow \nu_\mu$ allow measurements to be made of $\theta_{13}$, $\theta_{23}$ and $\Delta m_{\text{atm}}^2$, and, ultimately, for weak constraints to be placed on the CP-violating phase $\delta_{CP}$.

In addition to these analyses, T2K has made world-leading neutrino cross-section measurements in the sub-GeV energy range, utilising both the near and far detectors. The present work will discuss both the most recent measurements of the oscillation parameters, and these cross section analyses.

2 Neutrino oscillations

Observations of neutrino flavour change conclusively favour a model whereby the neutrinos have non-zero mass, and the mass eigenstates of the neutrino are not identical with the weak (flavour) eigenstates. Instead they are related by a unitary transformation, known as the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix $U_{\text{PMNS}}$:

$$
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix}
= U_{\text{PMNS}}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}.
$$

(1)

Since a neutrino produced in a specific weak eigenstate $\nu_\alpha$ is in a superposition of mass, and therefore energy, eigenstates, then after propagating some distance the different phases between the mass states will produce a superposition of flavour states. The neutrino may therefore be observed in a different flavour state $\nu_\beta$. The probability for a neutrino produced in a flavour eigenstate $\nu_\alpha$ to be observed later in a flavour eigenstate $\nu_\beta$, depends on the
neutrino energy $E$, the propagation distance $L$, the mass splittings between the eigenstates, $\Delta m_{ij}^2 \equiv m_j^2 - m_i^2$, as well as on the elements $U_{\alpha i}$ of the mixing matrix, as

$$P(\nu_\alpha \rightarrow \nu_\beta) = \delta_{\alpha\beta} - 4 \sum_i \sum_{j \leq i} \Re \left( U_{\alpha i} U_{\beta i} U_{\alpha j} U_{\beta j}^* \right) \sin^2 \left( \frac{\Delta m_{ij}^2 L}{4E} \right)$$

(2)

$$+ 2 \sum_i \sum_{j \leq i} \Im \left( U_{\alpha i} U_{\beta i} U_{\alpha j} U_{\beta j}^* \right) \sin \left( \frac{\Delta m_{ij}^2 L}{2E} \right).$$

This unitary transformation may be written as the product of three two-dimensional rotations with angles ($\theta_{12}, \theta_{13}, \theta_{23}$), with the addition of a complex phase $\delta_{CP}$, and CP-violation will be present unless $\delta_{CP}$ is equal to 0 or $\pi$. The additional degrees of freedom in the unitary transformation correspond to phases which are of no consequence for oscillation physics. Specifically, the matrix may be factorised thus:

$$U_{\text{PMNS}} = \begin{pmatrix}
1 & 0 & 0 \\
0 & c_{13} & s_{13} \\
0 & -s_{13} & c_{13}
\end{pmatrix} \begin{pmatrix}
c_{12} & s_{12} & 0 \\
0 & 1 & 0 \\
-s_{12} & c_{12} & 0
\end{pmatrix} \begin{pmatrix}
c_{23} & s_{23} & 0 \\
0 & 1 & 0 \\
0 & 0 & 1
\end{pmatrix},$$

(3)

where $(s_{ij}, c_{ij})$ correspond respectively to the sin and cosine of the angle $\theta_{ij}$. For the case of T2K, it is informative to write the oscillation probabilities in terms of these mixing angles, neglecting terms containing $\Delta m_{12}^2$, since at T2K energies and baselines, $\Delta m_{12}^2 L/E \ll 1$. This leads to the simplified expressions

$$P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - \sin^2(2\theta_{23}) \sin^2 \left( \frac{\Delta m_{23}^2 L}{4E} \right)$$

(4)

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

(5)

It can be seen that when considering only terms in $\Delta m_{23}^2$, the $\nu_\mu$ survival probability depends only on the angle $\theta_{23}$, and the $\nu_e$ appearance probability on $\theta_{13}$ and $\theta_{23}$. Dependencies on $\theta_{12}$, $\delta_{CP}$, and extra terms due to the presence of matter, appear only at higher orders.

### 3 The T2K Experiment

T2K is a long-baseline neutrino oscillation experiment based in Japan [1]. A beam of muon neutrinos is produced at the J-PARC facility using 30 GeV protons from the Main Ring (MR) accelerator, in a conventional fashion. The protons are extracted and impacted onto a target to produce a secondary beam containing mostly $\pi$ and $K$, which are then focused using a series of three magnetic horns, whose polarity can be changed to focus positive or negative hadrons, producing a dominantly $\nu_\mu$ or $\bar{\nu}_\mu$ beam respectively. Neutrinos are produced in the decays of hadrons; the dominant process for a $\nu_\mu$ beam is $(\pi^+ \rightarrow \mu^+ + \nu_\mu)$. Due to the presence of other decays and wrong-sign hadrons in the beam, an admixture of electron neutrinos, and wrong-sign muon neutrinos, is also present.
The T2K experiment is novel in that the main detectors are placed approximately 2.5° from the axis of the neutrino beam, giving a narrow-band beam with neutrino energies tightly focused around 600 MeV, the energy of the first oscillation maximum at the far detector. It also removes most of the high-energy tail of the beam, reducing the background from high-energy deep inelastic and resonant π production events, which can be mis-reconstructed as quasi-elastic events at a lower energy.

The far detector for T2K is the Super-Kamiokande water Cherenkov detector, at Mozumi Mine near Kamioka, on the west coast of Japan. Super-K is 295 km from J-PARC, and has a rock overburden of 1 km (2.7 km water equivalent), reducing non-beam backgrounds to a negligible level. It has a 50 kt total water mass, and 22.5 kt fiducial mass. The detector is cylindrical and split into an inner detector (ID) and outer veto region (OD), both instrumented with PMTs. Neutrino interactions are identified by observing the Cherenkov radiation from the resultant charged lepton; muons and electrons are distinguished by the different ring shapes produced, with muons producing a clean ring, and electrons a fuzzy ring due to showering.

A near detector complex at the J-PARC site, 280 m from the target, is used to constrain the properties of the unoscillated neutrino beam. It consists of an on-axis component (INGRID) and a detector at the same off-axis angle as Super-K (ND280). The INGRID consists of thirteen $1 \times 1 \times 1$ m$^3$ iron-plastic scintillator sampling calorimeter modules arranged in a plus configuration centred on the beam axis, with two additional off-diagonal modules. Its purpose is to measure the overall intensity and direction of the beam.

The ND280 detector is a general-purpose detector comprising multiple components. At the upstream end there is a module (the P0D) optimised for reconstruction of π$^0$ events. Downstream of this is a tracker region, consisting of two fine-grained scintillator detectors (FGDs) which make up the target mass, sandwiched between three gas TPCs. Surrounding the inner detectors are electromagnetic sampling calorimeters (ECALs), and a 0.2 T magnet to allow reconstruction of the momentum and sign of charged particles in the TPCs. The yoke of the magnet is instrumented with side muon range detectors (SMRDs), which also serve as a cosmic trigger.

The results presented in this paper are based on data taken in the period 2010–2013 (Runs 1–4). This period corresponds to a total of $6.6 \times 10^{20}$ 30 GeV protons on target. T2K is presently gathering $\nu_\mu$ data for analysis.

4 Flux constraint from beam simulation and ND280

The nominal beam flux, including admixtures, is modelled using a Monte Carlo, which uses GEANT3 to track hadrons through the target and horns, and internally implements the relatively simple propagation and decay of particles in the beam pipe. Results of the NA61 hadron production experiment at CERN are used to constrain hadron production in the target.

Results from the ND280 are used to tune the nominal Monte Carlo. The analysis used for this tuning is based on identifying and classifying charged-current (CC) interactions of muon neutrinos in the most upstream FGD of the detector. $\nu_\mu$-CC events are tagged
by looking for a vertex in FGD1, where the highest-energy negative track in the TPC immediately downstream has energy deposition consistent with a muon. These events are then classified as CC-0π, CC-1π+ or CC-other, based on the pions identified in the final state. Charged pions are tagged by pion-like TPC tracks, or, for positive pions, Michel electrons in FGD1. Neutral pions are tagged using electron-like tracks in the TPC. Any event containing multiple pions, or a π0 or π−, falls into the CC-other category. Figure 1 shows the momentum spectra for all events in these categories, both in data and nominal Monte Carlo.

![Figure 1: νµ-CC event spectra in the ND280, for data and nominal Monte Carlo](image)

The beam Monte Carlo parameters and cross-section models, with prior external constraints, are fitted to the three ND280 samples, to calculate the expected event rate at Super-K. The resulting improvement in event rate predictions can be seen in Figure 2.

![Figure 2: Predicted event spectra at Super-K, before and after constraints from fitting to ND280 data. Shown for νe (a) and νµ (b).](image)

5 Muon neutrino disappearance analysis

Muon neutrino disappearance at T2K is observed via a deficit in the number of νµ events seen at Super-K relative to that predicted in the absence of oscillations. This deficit is
expected to be energy-dependent, and enables measurements of $\theta_{23}$ and $\Delta m^2_{23}(\Delta m^2_{31})$ for normal(inverted) hierarchy (i.e. the sign of the mass splitting $\Delta m^2_{23}$), hereafter referred to as NH or IH.

A cuts-based analysis is used to obtain an event sample enriched with CCQE events ($\nu_\mu + n \rightarrow \mu^- + p$). The proton is usually below the Cherenkov threshold and therefore invisible. The analysis demands a single ring, with muon-like PID, vertex and whole event in the fiducial volume, low activity in the OD, visible energy $> 30$ MeV, reconstructed $p_\mu > 200$ MeV, and $\leq 1$ decay electron. The event must be in time with the beam. For selected events, the neutrino energy is reconstructed assuming that the underlying neutrino interaction is quasi-elastic. Oscillation parameters are estimated from this selection using an unbinned maximum-likelihood fit to the events. A full three-flavour fit, including matter effects, is performed. The oscillation parameters $\Delta m^2_{23}(\Delta m^2_{31})$ for NH(IH), $\delta_{CP}$ and $\sin^2 \theta_{23}$ are allowed to float freely in the fit. $\sin^2 \theta_{13}$, $\sin^2 \theta_{12}$ and $\Delta m^2_{21}$ are fitted with external constraints from reactor and solar+KamLAND data. 45 systematic parameters are included in the fit, from cross section uncertainties common with ND280 and specific to Super-K, Super-K detector effects, final state (FSI) and secondary (SI) interactions, and the aforementioned constrained oscillation parameters. The systematic errors from these sources are broken down in Table 1.

| Source of uncertainty (number of parameters) | $\delta n^\text{exp}_{SK}/n^\text{exp}_{SK}$ |
|---------------------------------------------|------------------------------------------|
| ND280-independent cross section (11)        | 4.9%                                     |
| Flux & ND280-common cross section (23)      | 2.7%                                     |
| SK detector & FSI+SI systematics (7)         | 5.6%                                     |
| $\sin^2 \theta_{13}$, $\sin^2 \theta_{12}$, $\Delta m^2_{21}$, $\delta_{CP}$ (4) | 0.2%                                     |
| Total (45)                                  | 8.1%                                     |

Table 1: Effect of 1σ systematic parameter variation on the number of 1-ring $\mu$-like events, computed for oscillations with $\sin^2 \theta_{23} = 0.500$ and $|\Delta m^2_{32}| = 2.40 \times 10^{-3}$ $eV^2/c^4$.

Figure shows the central values and 2D confidence regions for $\theta_{23}$ and $\Delta m^2_{23}(\Delta m^2_{31})$ for NH(IH), along with 90% C.L. limits for MINOS and Super-K for comparison. Confidence regions are calculated using the Feldman-Cousins technique. The best fit values and 1D 68% C.L. intervals are $\sin^2 \theta_{23} = 0.514^{+0.055}_{-0.056}(0.511 \pm 0.055)$ and $\Delta m^2_{23} = 2.51 \pm 0.10 \times 10^{-3}$ $eV^2/c^4(\Delta m^2_{31} = 2.48 \pm 0.10 \times 10^{-3}$ $eV^2/c^4$) for NH(IH). The error budget is dominated by statistical errors.
Figure 3: Oscillation best fit point and confidence regions for the T2K $\nu_\mu$ analysis, with MINOS and Super-K results for comparison. External constraints on other oscillation parameters are: $\sin^2 \theta_{13} = 0.0251 \pm 0.0035$, $\sin^2 \theta_{12} = 0.312 \pm 0.016$, $\Delta m^2_{21} = (7.50 \pm 0.20) \times 10^{-5}$ eV$^2$/c$^4$. $\delta_{CP}$ is unconstrained and a uniform Earth matter density of 2.6 g/cm$^3$ is used.

missed. The analysis allows measurement of $\sin^2 2\theta_{13}$.

The $\nu_e$ selection at Super-K is made using similar preselection cuts as for the $\nu_\mu$ analysis, on event timing, vertex location and event containment, visible energy and OD activity. As with the $\nu_\mu$ analysis, a CCQE-enriched sample is obtained by selecting events containing a single electron-like ring, with reconstructed momentum greater than 100 MeV/c. Events with a reconstructed neutrino energy (assuming CCQE kinematics) greater than 1250 MeV are also rejected, since these are dominantly due to the intrinsic $\nu_e$ beam component. To remove $\pi^0$ background, an algorithm measuring the maximum likelihood of the observed PMT hit pattern, assuming $\nu_e$-CCQE or NC-$\pi^0$, is used; events are accepted or rejected based on the reconstructed $\pi^0$ mass and the likelihood ratio between the $\pi^0$ and electron hypothesis best fits. These cuts lead to an expected 21.6 selected events for $\sin^2 2\theta_{13} = 0.1$ and $\delta_{CP} = 0$; the expected number for $\theta_{13} = 0$ is 4.92. In actuality, 28 candidate events were observed. The total systematic error on the number of observed events is 8.8% for $\sin^2 2\theta_{13} = 0.1$; this is dominated by neutrino cross-section uncertainties.

A binned extended maximum-likelihood fit is used to extract oscillation parameters from the data. The likelihood function contains terms for the signal shape, signal normalisation, T2K systematics and external oscillation constraints. Events are parameterised using the reconstructed electron momentum and angle; however, parameterising events using reconstructed neutrino energy gives compatible best-fit points and near-identical confidence regions. Other oscillation parameter inputs are as follows: $\sin^2 \theta_{12} = 0.306$, $\Delta m^2_{21} = 7.6 \times 10^{-5}$ eV$^2$, $\sin^2 \theta_{23} = 0.5$, $|\Delta m^2_{32}| = 2.4 \times 10^{-3}$ eV$^2$, $\delta_{CP} = 0$. For the NH(III) the best-fit values, and 68% confidence level bounds, are $\sin^2 2\theta_{13} = 9.140^{+0.036}_{-0.032}(0.170^{+0.045}_{-0.037})$. The significance of non-zero $\theta_{13}$ is found to be 7.3$\sigma$; the same result is obtained with either a delta log-likelihood method or toy Monte Carlo. This significance was obtained using the values for $\sin^2 \theta_{23}$ and $\delta_{CP}$ as above; however the significance remains above 7.0$\sigma$ for any values of these parameters consistent with their uncertainties. The $\sin^2 2\theta_{13}$ confidence
limits are shown as a function of $\delta_{CP}$ in Figure 4.

![Figure 4: Oscillation best fit point and confidence regions for the T2K $\nu_e$ analysis.](image)

$\pi(n) (CP, \delta)$

$\sigma_{PDG2012}$

$\Delta m^2_{\nu\nu}$

$0.0$ $0.05$ $0.1$ $0.15$ $0.2$ $0.25$ $0.3$ $0.35$ $0.4$

$\sin^2 \theta_{13}$

7 Cross section measurements

The T2K experiment is making world leading neutrino cross section measurements in the $\sim 1$ GeV range. Only results and outlines of the analyses will be presented here; the reader is directed to the references given for detailed descriptions.

7.1 $\nu_e$ CC-inclusive cross section on Carbon

The CC-inclusive cross section of $\nu_e$ on Carbon has been measured in the ND280 detector [4]. The signal for this process is any event containing an electron in the final state, and the principal background is $\gamma$s from $\pi^0$ decay.

Events are selected which have a negative electron-like track (by $dE/dx$) in TPC2, with a vertex in FGD1. Events are subject to a veto on activity upstream of FGD1. The $\pi^0$ background is reduced by demanding that events containing a positive track do not have an invariant mass compatible with a $\pi^0$ when the track is matched with the electron candidate.

Figure 5 (a-c) show the differential cross sections (averaged over the T2K flux), as a function of electron momentum, interaction $Q^2$, and the cosine of the electron polar angle, respectively. Good agreement is seen between T2K and the generators for the differential cross sections. Figure 5 (d) shows the measured cross section, integrated over the T2K beam flux, along with results from the Gargamelle bubble chamber experiment and the NEUT and GENIE Monte Carlo interaction generators; again, good agreement is seen with the generators, and also the Gargamelle data.
Figure 5: $\nu_e$-CC cross sections on Carbon, integrated over the T2K beam flux. (a-c) show differential cross sections in electron momentum, interaction $Q^2$, and the cosine of the electron polar angle, respectively. (d) shows the total cross section.

7.2 $\nu_\mu$ CC-inclusive cross section on Carbon

The ND280 detector has also measured the $\nu_\mu$ CC-inclusive cross section on Carbon [5]. The selection for this measurement is essentially identical to that used for the analysis constraining systematics for Super-K (see Section 4). All $\nu_\mu$-CC candidate events are included in the selection.

The events are binned in muon momentum $p_\mu$ and polar angle $\cos \theta_\mu$, and differential cross sections are computed in these values, integrated over the beam flux. These results are shown in Figure 6 — the results agree well with the NEUT and GENIE generators.

7.3 NCQE cross section from de-excitation gammas

T2K has made the first ever measurement of neutral current quasi-elastic (NCQE) neutrino scattering on Oxygen [6]. This process, $\nu_x + ^{16}\text{O} \rightarrow \nu_x + p + ^{15}\text{N}^*$ (or $\nu_x + n + ^{15}\text{O}^*$), leaves the daughter nucleus in an excited state, so the events can be tagged using gamma rays from nuclear de-excitation. A beam with a low duty cycle, combined with precise timing information, allows to reduce the non-beam background to a negligible level, enabling a measurement which would be impossible with atmospheric neutrinos.

After making standard Super-K cuts to remove non-beam background, and vetoing on high-energy preceding events, events are selected which have a visible energy between 4 and...
Figure 6: $\nu_\mu$-CC cross sections on Carbon, integrated over the T2K beam flux. (a-d) each show the differential cross section in muon momentum, for a different range of muon polar angle.

20 MeV, and a large Cherenkov angle. This Cherenkov angle cut helps to remove low-energy muons from the event sample. After making these cuts, the dominant background is from NC non-QE events.

Figure 7 shows the measured cross section, averaged over the T2K beam flux. This is seen to be compatible with the Ankowski NCQE model over the flux energy range.

8 Summary

The T2K experiment has published results showing exclusion of $\theta_{13} = 0$ of 7.3$\sigma$ in the $\nu_e$ appearance channel, and giving the world’s most precise measurement of $\theta_{23}$. It has also produced world-leading neutrino cross section results using both near and far detectors.

9 Acknowledgments

I gratefully acknowledge the support of the STFC, which provides funding for my participation in the T2K project.
Figure 7: Measurement of the NCQE cross section for the T2K beam flux.

References

[1] K. Abe et al. [T2K Collaboration], Nucl. Instrum. Meth. A 659 (2011) 106 [arXiv:1106.1238 [physics.ins-det]].

[2] K. Abe et al. [T2K Collaboration], Phys. Rev. Lett. 112 (2014) 18, 181801 [arXiv:1403.1532 [hep-ex]].

[3] K. Abe et al. [T2K Collaboration], Phys. Rev. Lett. 112 (2014) 061802 [arXiv:1311.4750 [hep-ex]].

[4] K. Abe et al. [T2K Collaboration], Phys. Rev. Lett. 113 (2014) 241803 [arXiv:1407.7389 [hep-ex]].

[5] K. Abe et al. [T2K Collaboration], Phys. Rev. D 87 (2013) 9, 092003 [arXiv:1302.4908 [hep-ex]].

[6] K. Abe et al. [T2K Collaboration], Phys. Rev. D 90 (2014) 7, 072012 [arXiv:1403.3140 [hep-ex]].