Muon neutrino disappearance at T2K

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Abstract. The T2K experiment has observed the disappearance of muon neutrinos from the J-PARC muon-neutrino beam. Using data corresponding to 3.01 × 10\textsuperscript{20} protons on target, 58 muon neutrino event candidates were observed; 205 ± 17 (syst.) events are expected under the no-oscillation hypothesis. A fit to the observed rate and energy spectrum in a neutrino oscillation framework with three active neutrino flavours in constant density matter, assuming the normal mass hierarchy, yields a best fit mixing angle sin\(^2\theta_{23} = 0.514 ± 0.082\) and best fit mass squared splitting |\(Δm\textsuperscript{2}_{32}\)| = \(2.44\textsuperscript{+0.17}_{-0.15} \times 10^{-3}\text{ eV}^2/\text{c}^4\), which corresponds to the maximal disappearance probability.

T2K is an off-axis long-baseline neutrino experiment using the J-PARC muon-neutrino beam to study neutrino oscillation parameters. In the limit \(Δm\textsuperscript{2}_{21} ≪ |Δm\textsuperscript{2}_{32}|\), the probability of muon neutrino disappearance is

\[
P(ν_μ → ν_μ) ≃ 1 - 4\cos^2θ_13\sin^2θ_{23}[1 - \cos^2θ_13\sin^2θ_{23}]\sin^2(1.267Δm^2_{32}L/E_ν),
\]

where \(L(\text{km})\) is the neutrino propagation distance, \(E_ν(\text{GeV})\) is the neutrino energy, and \(Δm^2_{32}(\text{eV}^2/\text{c}^4)\) is the neutrino mass-squared splitting, \(Δm^2_{32} = m^2_3 - m^2_2\). From equation 1, it can be shown that maximal disappearance occurs at \(\sin^2θ_{23} ≃ 1/(2 - 2\sin^2θ_{13})\), and the disappearance probability is symmetric in \(\sin^2θ_{23}\) about this point. Using recent measurements of \(θ_{13}\) (sin\(^2(2θ_{13}) = 0.098\) [1]), maximal disappearance occurs at \(\sin^2θ_{23} ≃ 0.513\). Since maximal disappearance occurs at a point which is not the same as maximal 23-sector mixing (\(\sin^2θ_{23} = 0.500\)) it is also necessary to fit for \(\sin^2θ_{23}\), rather than the historically used \(\sin^2(2θ_{23})\), since the oscillation probability depends on the choice of octant (\(\sin^2θ_{23} < 0.5\) or \(\sin^2θ_{23} > 0.5\)).

The T2K experiment consists of a muon-neutrino beam, a suite of near detectors, and a far detector, Super-Kamiokande (SK). The muon-neutrino beam is generated using a 30 GeV proton beam produced at J-PARC. Three magnetic horns are used to focus charged pions and kaons produced in interactions of the beam with a graphite target, which then decay in a 96-m-long decay volume. SK is a 22.5 kt fiducial volume water Cherenkov detector located 2.5° off-axis and 295 km from the graphite target. The off-axis angle means SK sees a narrow-band neutrino beam, with energy \(E_ν ≃ 600\text{ MeV}\), corresponding to the first oscillation maximum at \(E_ν = 1.267Δm^2_{32}L/(2π)\). This enhances the sensitivity to the oscillation parameters by increasing the number of neutrinos that oscillate, and decreasing backgrounds from the high-energy tail. The unoscillated neutrino beam is sampled by ND280, a near detector 2.5° off-axis and 280 m from the graphite target, in order to constrain the flux and cross section models. Here we report the results of the \(ν_μ\) disappearance search with T2K Runs 1-3, consisting of 3.01 × 10\textsuperscript{20} protons on target [2].
Fits to external datasets are used to tune both the initial flux [3] and cross section [4] models, and to set the magnitude of the uncertainties. Simulations of proton beam interactions with the graphite target predict the neutrino fluxes at ND280 and SK, along with a covariance between neutrino energies, neutrino flavours, and detectors. Flux uncertainties are dominated by hadron production uncertainties, and are 10-20% in the flux peak region. There are two classes of cross section model parameters, those common between ND280 and SK, and those independent of ND280. This distinction is necessary because interactions at ND280 are predominately on carbon targets, whereas interactions at SK are predominately on oxygen targets. The ND280-common cross section systematics include axial mass parameters for charged current quasi-elastic (CCQE) and resonant pion production, and five normalisation parameters. The independent parameters include parameters controlling the CCQE nuclear model, pion production parameters, and normalisations for samples that are not included in the ND280 fit (including neutral current (NC), antineutrinos and electron neutrinos). A further set of model uncertainties from pion interactions within the nucleus (final-state interactions) and within the detector (secondary interactions) are assigned by varying model parameters to span external datasets.

An inclusive selection of $\nu_\mu$ CC events is performed at ND280 by searching for the highest-momentum negatively-charged track in the second time projection chamber (TPC2), requiring that the energy loss is consistent with a muon, and requiring it to start in the fiducial volume of the first fine grained detector (FGD1). A veto is applied on TPC1 activity, upstream of FGD1, to reject events with vertices upstream of FGD1. The inclusive sample is split into two subsamples based on the presence of a pion: the CCQE sample contains events with exactly one track matched between FGD1 and TPC2 and no delayed activity in FGD1 consistent with a Michel electron; the CCnonQE sample contains all other events. The purity of the CCQE and CCnonQE samples is 69.5% and 70.4% respectively. The absolute muon momentum scale, pion secondary interactions, and background uncertainties are the largest detector systematics.

The ND280 data are fit in 40 bins (5 momentum $\times$ 4 angular $\times$ 2 sample bins). ND280 flux parameters, both common and ND280 cross section parameters, and detector uncertainties are included in the fit, in order to constrain the flux and cross section models for the oscillation fit. The best-fit values of the 23 flux and common cross section parameters, and their covariance is used in the oscillation fit.

Muon neutrino CCQE events are selected at SK by searching for exactly 1 $\mu$-like Cherenkov ring in a fully-contained event with a fiducial volume vertex, with visible energy $> 30$ MeV, reconstructed muon momentum $> 200$ MeV, and $\leq 1$ reconstructed Michel electron. Timing cuts are also applied such that the event is consistent with the neutrino beam. Observed muon kinematics are used with the quasi-elastic formula to determine the reconstructed neutrino energy

$$E_{\text{reco}} = \frac{m_p^2 - (m_n - E_b)^2 - m_\mu^2 + 2(m_n - E_b)E_\mu}{2(m_n - E_b - E_{\mu} + p_\mu \cos \theta_\mu)},$$

(2)

where $p_\mu$, $E_\mu$, $\cos \theta_\mu$ are the reconstructed muon momentum, energy, and the angle with respect to the beam direction, respectively, $m_p$, $m_n$, and $m_\mu$ are the masses of the proton, neutron, and muon, respectively, and $E_b = 27$ MeV is the average binding energy of a nucleon in $^{16}$O. Under the no-oscillation hypothesis $205 \pm 17$ events are predicted, and the spectrum, shown in figure 1, is 77.7% pure in $\nu_\mu + \bar{\nu}_\mu$ CCQE events. SK detector systematics are assigned by comparing both cosmic muon and atmospheric neutrino data with Monte Carlo predictions. The largest uncertainties are due to ring counting, and particle identification for neutral current events.

The error on the number of events from the four error categories at SK is shown in table 1 for a typical oscillation point. The constraint provided by the ND280 fit results in a large reduction in the error (21.8% to 4.2%), resulting in the SK detector systematics dominating (10.1%).

A likelihood ratio fit is performed in order to estimate the oscillation parameters. The fit is performed with 73 variable-width reconstructed energy bins and 48 systematic parameters,
Using an oscillation probability generated for three active neutrino flavors in constant density matter of 2.6 g/cm$^3$. Other oscillation parameters are fixed: $\sin^2(2\theta_{13}) = 0.098$; $\Delta m^2_{21} = 7.5 \times 10^{-5}$ eV$^2$/c$^4$; $\sin^2(2\theta_{12}) = 0.857$ [1], $\delta_{CP} = 0$, and the normal mass hierarchy is assumed. The best-fit point is at $\sin^2\theta_{23} = 0.514 \pm 0.082$ and $|\Delta m^2_{32}| = 2.44^{+0.17}_{-0.15} \times 10^{-3}$ eV$^2$/c$^4$, and the best-fit spectrum is shown in figure 1. Confidence regions are constructed with the constant-$\Delta\chi^2$ method [1], and the 1-dimensional and 2-dimensional regions are shown in figure 2. This result corresponds to the maximum disappearance probability. In the time since this poster was presented, T2K has published new results using more than twice as much data, and an improved ND280 analysis [5].

References
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**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$^4$.

| Source of uncertainty (no. of parameters) | $\delta n^\text{exp}_{SK} / n^\text{exp}_{SK}$ |
|------------------------------------------|------------------------------------------|
| ND280-independent cross section (11)     | 6.3%                                     |
| Flux & ND280-common cross section (23)   | 4.2%                                     |
| (without ND280 fit) (23)                  | (21.8%)                                  |
| SK detector systematics (8)              | 10.1%                                    |
| Final-state and secondary interactions (6)| 3.5%                                     |
| Total (48)                               | 13.1%                                    |

**Figure 1.** Top: The 58 event 1 $\mu$-like ring SK reconstructed energy spectrum with the prediction for the no-oscillation hypothesis and the best-fit from the oscillation analysis. Bottom: The ratio of both the observed spectrum and best-fit curve to the no-oscillation hypothesis.

**Figure 2.** The 68% and 90% C.L. regions for $\sin^2\theta_{23}$ (top), $|\Delta m^2_{32}|$ (right), and $\sin^2\theta_{23}$ versus $|\Delta m^2_{32}|$ (bottom left).