First measurements of muon anti-neutrino disappearance by the T2K experiment

Takahiro HIRAKI* **for the T2K collaboration**
Kyoto University
E-mail: `hiraki@scphys.kyoto-u.ac.jp`

The T2K experiment is a long-baseline neutrino oscillation experiment. Last year we started to take data with anti-neutrino beam. In this poster proceedings the first result of $\overline{\nu}_\mu$ disappearance analysis is shown. We fit the muon-like events observed at Super-Kamiokande when running in anti-neutrino mode to estimate the oscillation parameters of the PMNS model. We describe the analysis overview and present systematic errors, preliminary confidence intervals and best-fit points obtained with anti-neutrino mode data.

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*Speaker.

1. Introduction

The T2K experiment is a long-baseline neutrino oscillation experiment [1]. An intense muon neutrino beam is produced by striking 30 GeV protons on a graphite target, producing secondary hadrons which are focused by magnetic horns. The produced neutrinos are measured by the off-axis near detectors (ND) at J-PARC and by the Super-Kamiokande detector (SK), which is 295 km away from J-PARC.

Using the data collected until 2013, T2K published measurements of ν_μ disappearance and ν_e appearance with a world-leading precision [2]. In 2014 we started to take data with $\overline{\nu}$ beam. The $\overline{\nu}$ beam is obtained by focusing π^-'s with 3 electromagnetic horns.

In this poster proceedings we report the first result of $\overline{\nu}_\mu$ disappearance analysis. One-ring muon-like events at SK are selected. In this analysis, to see potential effects coming from a new physics like the CPT violation or non-standard interactions, we treat (θ_{23}, Δm^2_{32}) for neutrinos and ($\overline{\theta}_{23}$, $\Delta\overline{m}^2_{32}$) for anti-neutrinos as independent parameters and fit data with ($\overline{\theta}_{23}$, $\Delta\overline{m}^2_{32}$).

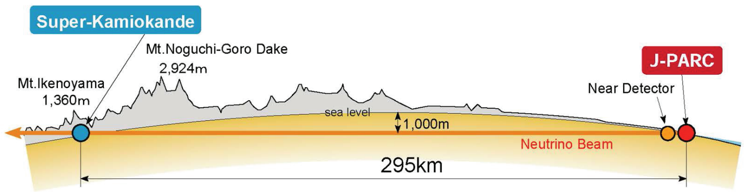

Figure 1: Schematic view of the T2K experiment

2. Analysis overview

The analysis is carried out by comparing the observed data to the prediction assuming neutrino oscillation for a given set of values of the neutrino oscillation parameters. The energy spectrum at SK is first predicted with the neutrino flux and the neutrino-nucleus interaction cross section, both of which are modeled based on external data. The ND data including both ν-mode and $\overline{\nu}$-mode data is then used to refine the prediction at SK.

As mentioned in the introduction, we treat (θ_{23}, Δm^2_{32}) for neutrinos and ($\overline{\theta}_{23}$, $\Delta\overline{m}^2_{32}$) for anti-neutrinos as independent parameters. The other oscillation parameters are assumed to be the same for neutrinos and anti-neutrinos and these values are fixed and taken from the ν-mode results from T2K [2] and the Particle Data Group 2014 [3].

In this analysis an extended maximum likelihood method is used. The likelihood is defined as:

$$\mathscr{L}(N_{obs}, x, o, f) = \mathscr{L}_{norm}(N_{\text{obs}}, o, f) \times \mathscr{L}_{shape}(N_{\text{obs}}, x, o, f) \times \mathscr{L}_{\text{syst}}(f) \tag{2.1}$$

where

- N_{obs} is the number of 1-Ring μ-like candidate (1Rμ) events observed in SK
- x represents the reconstructed energy of each event

- o represents the oscillation parameters we are trying to measure ($\overline{\theta}_{23}$ and $\Delta\overline{m}^2_{32}$)
- f corresponds to the nuisance parameters describing systematic uncertainties.

$\mathscr{L}_{norm}$ is the normalization term of the likelihood and the probability follows a Poisson distribution. $\mathscr{L}_{shape}$ is the shape term, and uses the information coming from the shape of the distribution of the reconstructed energy. $\mathscr{L}_{\mathrm{syst}}$ is the systematic term of the likelihood. Systematic parameters used in the analysis are described in Section 3.

Expected 1Rμ events at SK with 2.3×10^{20} protons-on-target (POT) data are listed in Table. 1. Here $(\theta_{23}, \Delta m^2_{32}) = (\overline{\theta}_{23}, \Delta\overline{m}^2_{32})$ is assumed. Due to the good particle identification capability of the SK detector, ν_e and $(\overline{\nu}_e)$ contamination are small. Compared to the ν-mode case, the fraction of wrong-sign contamination (ν_μ) is larger mainly because anti-neutrino cross section is much smaller than neutrino cross section.

Table 1: expected 1-Ring μ-like events at SK with 2.3×10^{20} POT data

	$\overline{\nu}_\mu$	ν_μ	$\nu_e+\overline{\nu}_e$	total
no oscillation	45.4	14.3	0.06	59.8
maximal disappearance	12.2	7.7	0.08	19.9

3. Systematic uncertainties

As sources of systematic error, the neutrino flux in each flavor, neutrino-nucleus interaction, SK detector, final state interaction of hadrons inside nucleus (FSI) and secondary interaction (SI) are considered.

Table 2 summarizes the uncertainties on number-of-event prediction, where those obtained without or with constraints by the measurement in ND are shown. The uncertainties on the neutrino flux and some cross section parameters are well-constrained by ND data. The dominant systematic uncertainties come from the interaction which could not constraint by the ND measurement because of the difference of the materials between ND (carbon) and SK (oxygen). In near future these errors are expected to be decreased by analyzing ν-oxygen interaction data in ND.

Table 2: Fractional and total systematic uncertainties with and without ND measurement

Error source	1σ	
	without ND measurement	with ND measurement
flux	7.1%	3.5%
cross section common to ND	5.8%	1.4%
flux $\times$ cross section common to ND	9.2%	3.4%
cross section (SK only)	10.0%	
SK detector	3.8%	
SK FSI and SI	2.1%	
All	14.4%	11.6%

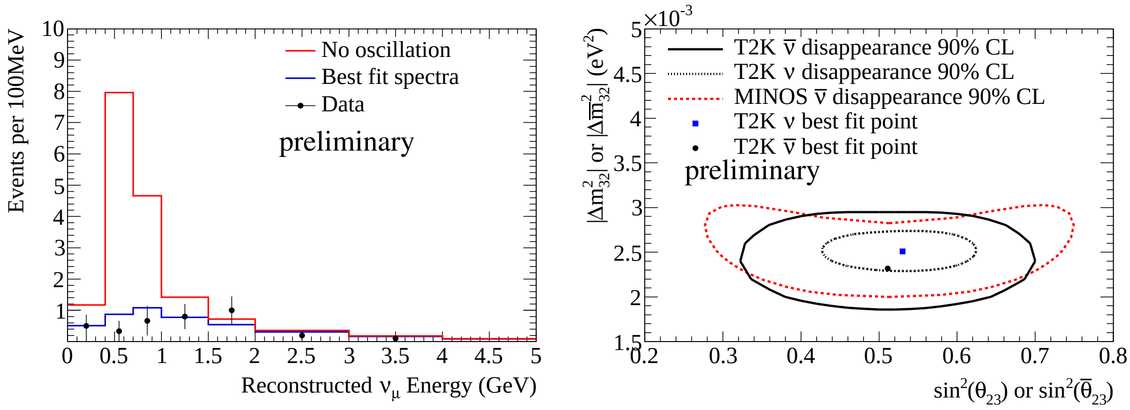

Figure 2: The left plot is the best-fit reconstructed energy spectrum with data points. The right plot is the confidence interval for ν-mode and $\overline{\nu}$-mode data.

4. Oscillation results

We observed 17 1-Ring μ-like events at SK using 2.3×10^{20} POT data. The expected number without oscillation effect is approximately 60. Thus, clear disappearance is observed.

Figure 2 shows the **preliminary** result of the fit of ($\overline{\theta}_{23}$, $\Delta\overline{m}^2_{32}$) and the best-fit reconstructed energy spectrum in the normal hierarchy.

We obtained the following **preliminary** best fit and 1σ confidence interval:

($\sin^2(\overline{\theta}_{23})$, $|\Delta\overline{m}^2_{32}|$)=($0.51\pm0.10$, $2.32\pm0.23\times10^{-3}(\mathrm{eV}^2)$). The best-fit ($\overline{\theta}_{23}$, $\Delta\overline{m}^2_{32}$) is consistent with ($\theta_{23}$, Δm^2_{32}) from the latest T2K ν-mode measurements. The confidence interval in $\overline{\nu}$ mode is wider due to lower statistics and larger background.

This result gives a compatible measurement with what was achieved by the MINOS experiment [4].

5. Conclusion

The T2K experiment has been taking anti-neutrino mode data since 2014. First measurements of $\overline{\nu}_\mu$ disappearance with a dataset corresponding to 2.3×10^{20} POT has been conducted. We obtained the following **preliminary** best fit and 1σ confidence interval: ($\sin^2(\overline{\theta}_{23})$, $|\Delta\overline{m}^2_{32}|$)=($0.51\pm0.10$, $2.32\pm0.23\times10^{-3}(\mathrm{eV}^2)$). This result is consistent with the measurement of (θ_{23}, Δm^2_{32}) with T2K ν-mode data [2].

References

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