Study of neutrino interactions at the T2K near detector

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Abstract. The Tokai-To-Kamioka (T2K) experiment was designed to measure the oscillation of muon neutrinos produced at the J-PARC accelerator in Japan. The Super-Kamiokande detector acts as the far detector and a near detector is installed in the path of the neutrino beam to reduce uncertainties on the flux and cross sections. This near detector, called ND280, is located 280 m from the production target of the T2K neutrino beamline in order to measure the characteristics of the beam prior to any oscillation. The first ND280 analysis of the momentum-angle distribution of the muon produced by muon neutrino charged current interactions has been performed. These results have also been used to determine a flux-averaged cross section.

1. Introduction
The T2K experiment was designed to measure the oscillation of muon neutrinos produced at the J-PARC facility in Tokai, Japan. The disappearance of muon neutrinos and appearance of electron neutrinos are measured in the Super-Kamiokande detector (SK) acting as the far detector. The T2K complex also includes near detectors located 280 m from the production target. One of these detectors is ND280, which is located in the path of the neutrinos going to Super-Kamiokande. The role of ND280 is to measure the characteristics of the unoscillated neutrino beam such as the energy spectrum and also the interaction rate.

The main purpose of the ND280 muon neutrino measurement is to constrain the flux and cross section parameters of the T2K neutrino oscillation analysis in order to reduce systematic uncertainties. The ND280 results can also be used to measure the differential cross section to test the cross section models used by T2K and other neutrino experiments.

2. The apparatus
ND280 is a complex of multiple subdetectors all installed inside the magnet from the UA1 experiment, which provides a 0.2 T magnetic field [1] (Fig. 1). The subdetectors used in the analysis presented in this paper are the two fine-grained detectors (FGDs) [3] and the three time projection chambers (TPCs) [2] which together are referred to as the tracker. The FGDs are composed of alternating vertical and horizontal layers of 1 cm$^2$ square extruded polystyrene scintillator bars read out by wavelength-shifting fibers. The purpose of the FGDs is to act as active targets and provide detailed vertex information of the neutrino interactions. FGD1 is composed entirely of scintillator layers while FGD2 contains scintillator and water layers in order to compare the neutrino interaction rate on carbon and on oxygen. FGD1 and FGD2 are...
located respectively between TPC1 and TPC2, and TPC2 and TPC3. The TPCs are filled with an argon, CF₄, and isobutane gas mixture at respectively 95, 3, and 2% and use MicroMegas detectors for gas amplification with pad readout. The TPCs are used to reconstruct the charged particle’s momentum with an inverse momentum resolution of 0.1 (GeV/c)^−1. The TPCs are also capable of particle identification using the energy loss to distinguish in particular muons from electrons with a misidentification probability of < 0.9% from 200 MeV/c to 1.8 GeV/c.

ND280 also contains, upstream of the tracker, the P0D which is dedicated to π₀ reconstruction and made of scintillator bars interleaved with lead and brass sheets. The tracker and the P0D are surrounded by electromagnetic calorimeters (ECals) composed of layers of plastic scintillator bars with lead sheets in between.

3. The ND280 muon neutrino measurement

The analysis of the ND280 data to extract the muon neutrino beam properties starts by selecting all the charged current (CC) interactions occurring in the FGD1 detector. In each event, the highest-momentum negative track is the muon candidate track. The selected events have the following requirements: they have no track in TPC1, their muon candidate track originates from the FGD1 fiducial volume, and the particle identification from the TPCs for the candidate track is consistent with the muon hypothesis. This CC interaction sample is split into a charged current quasi-elastic (CCQE) sample, and a charged current non quasi-elastic (CCnQE) sample for interactions in which at least one pion was produced. Events in the CCQE sample have only one TPC-FGD track and no Michel electron in FGD1, originating from the decay of a pion stopped in FGD1 producing a muon, and then an electron. The Michel electrons are identified using timing information in FGD1.

The results presented in this paper use only the data from 2010 and 2011, however the consistency of these data with the 2012 data was tested and confirmed. Momentum-angle spectra are produced for the CCQE and CCnQE samples. The main physics application of these results is to estimate beam and neutrino interaction properties with a maximum likelihood fit of the ND280 data along with the beam flux prediction and external cross section data as constraints. The results of the fit and the high correlation between the ND280 and SK fluxes provide a significant reduction of the beam and cross section systematic uncertainties in the SK neutrino

Figure 1. Schematics of ND280 in the opened magnet position.
interaction rate prediction. The CCQE and CCnQE samples were split in the ND280 analysis to allow the CCQE sample to constrain the spectral shape, the flux and cross section parameters, while the CCnQE sample constrains backgrounds and cross section parameters. The momentum projection of the CCQE and CCnQE spectra prior to the fit (Fig. 2 and 3) display already a good agreement between data and MC.

**Figure 2.** Momentum distribution of muon from selected CCQE interactions for data and simulation.

**Figure 3.** Momentum distribution of muons from selected CCnQE interactions for data and simulation.

### 4. Cross section measurement

In addition to constraining flux and cross section parameters for the neutrino oscillation measurement, the ND280 results can be used to perform a flux-averaged differential cross section measurement.

For this analysis, the CC inclusive sample containing both the CCQE and CCnQE samples is used to have a data sample as large as possible. The cross section is measured from the momentum-angle spectrum using:

\[
\langle \frac{\partial^2 \sigma}{\partial p_\mu \partial \cos \theta_\mu} \rangle_{kl} = \frac{N_{kl}^{\text{int}}}{T \phi \Delta p_{\mu,k} \Delta \cos \theta_{\mu,l}}
\]

with \(N_{kl}^{\text{int}}\) the number of true interactions in the true bin \(kl\), \(T\) the number of target nucleons, \(\phi\) the flux, \(p_\mu\) the muon momentum, and \(\cos \theta_\mu\) the angle between the muon direction and the neutrino beam axis. In order to obtain \(N_{kl}^{\text{int}}\), we unfold the momentum-angle resolution from the measured CC inclusive spectra using an iterative method based on the Bayes’ theorem [4]. A migration matrix derived from the simulation converts the reconstructed bins into true bins and a correlation matrix is used to propagate the systematic uncertainties of each bin. The measured differential cross section is compared in Fig. 4 to the predictions from the two neutrino interaction generators used in T2K called NEUT [5] and GENIE [6]. The integrated cross section is:

\[
\langle \sigma_{\text{CC}} \rangle_\phi = (6.93 \pm 0.13(\text{stat.}) \pm 0.85(\text{syst.})) \times 10^{-39} \text{cm}^2/\text{nucleons.}
\]

Similarly the predictions from NEUT and GENIE are respectively:

\[
\langle \sigma_{\text{CC}}^{\text{NEUT}} \rangle_\phi = 7.26 \times 10^{-39} \text{cm}^2/\text{nucleons,}
\]
\[
\langle \sigma_{\text{CC}}^{\text{GENIE}} \rangle_\phi = 6.68 \times 10^{-39} \text{cm}^2/\text{nucleons.}
\]
The measurement is limited by the flux and detector systematic uncertainties. Future flux determination will use the 2009 data set from the NA61 experiment, which used a graphite target similar to the one used in the T2K beamline [7], and therefore the flux uncertainties will be reduced. Also improvements in the ND280 software will provide better track reconstruction and reduced detector systematic uncertainties.

![Graphs showing differential cross sections](image)

**Figure 4.** Flux-averaged differential cross section in momentum of the outgoing muon for each angle bin, for data and for the two neutrino interaction generators NEUT and GENIE.

5. Future analysis developments

New extensions of the ND280 analysis are already being developed in order to increase the constraints on the flux and cross section parameters used in the oscillation measurement. The first approach is to use the muon and the proton tracks in the CCQE interactions instead of just identifying the muon track. A more detailed study of the CCQE interaction will be possible starting with the neutrino energy, which will be reconstructed from both particles, eliminating the need for assumptions on the neutron kinematics. This analysis will also have a stronger discrimination between neutrino interaction models since it will test the modelling of both the muon and the proton.

The other improvement will be the measurement of the CC1π interaction, which is a significant background of the CCQE measurement in SK due to the pion absorption. Furthermore this measurement will complement the MiniBooNE data measured for neutrinos around 1 GeV of energy. This analysis starts from the CCnQE sample and uses additional selections to identify events with one pion. The TPC particle identification is used when the
pion reaches the TPCs. The possibility to identify the pions in the FGDs or the ECals is being investigated for event topologies where the pion did not reach a TPC.

6. Conclusion
The T2K near detector has demonstrated its important role in the neutrino oscillation measurement by providing momentum-angle distributions for CCQE and CCnQE interactions. The results from ND280 have also been used for a stand-alone cross section measurement of CC interactions. The current results correspond only to a few percent of the statistics goal of the T2K experiment. Furthermore calibration, software, and analysis improvements have already been implemented and more are in development.

References
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