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Analysis of muon and electron neutrino charged current interactions in the T2K near detectors

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Abstract

We present the updated measurement of the muon neutrino interaction rates and spectrum at the T2K near detector complex, ND280, located at the JPARC accelerator facility in Tokai, Japan, 280 meters downstream from the target. The measurements are obtained using all the data collected until 2014. The momentum-angle spectrum of muons from ν_μ charged current (CC) interactions measured at ND280 off-axis detector constrains the flux and cross-section uncertainties in the T2K oscillation analysis. This spectrum was also used to measure a differential cross-section measurement of muon neutrinos on carbon. Similarly the ν_e contamination of the T2K beam was measured to verify this intrinsic background for the electron neutrino appearance and provide the first electron neutrino cross-section result since the Gargamelle experiment. The ν_μ CC inclusive events selected in the on-axis detector (INGRID) at 280 m and originally used for monitoring the T2K beam stability were also used to measure the CC interaction cross sections on carbon and iron. The selections and results for both ND280 and INGRID will be presented in this paper as well as future prospects for both detectors.

Keywords: T2K, electron neutrinos, muon neutrinos, near detectors, cross section, carbon, iron

1. Introduction

The discovery of neutrino oscillation has marked the beginning of a new era for neutrino physics focussed on the determination of the mixing angles of the PMNS mixing matrix and the neutrino mass differences. Only recently the θ_{13} angle was shown to be non-zero using anti-electron neutrino disappearance in Daya bay and RENO and also from the first ever observation of electron neutrino appearance in T2K. This marks the beginning of the search for the CP violation phase in the neutrino sector since θ_{13} has to be non-zero for the CP violation to be observable in neutrino oscillation.

The precise measurement of the CP violation phase will require a new generation of long baseline experiments with increased beam power and well chosen baseline for optimal sensitivity. These experiments will also need to achieve an unprecedented level of understanding of the neutrino beam flux and neutrino cross-section uncertainties. The latter will require theoretical developments, in particular in understanding the nuclear effects involved in neutrino-nucleus interactions, and also a dedicated experimental effort with neutrino cross-section measurements at various energies and on various nuclear targets. Although primarily designed to observe neutrino oscillation, the near detectors of the T2K experiment can contribute to this experimental effort in particular because they are composed of multiple detectors offering multiple nuclear targets located at different energies in the T2K neutrino beam.

2. The T2K experiment

In T2K, a beam of muon neutrinos is produced at the J-PARC facility in Tokai, Ibaraki, Japan, and it is

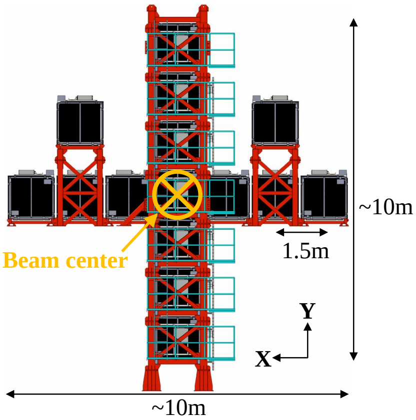

Figure 1: Schematics of the INGRID apparatus. The central cross is composed of 7 standard modules in the horizontal segment, and 7 in the vertical one.

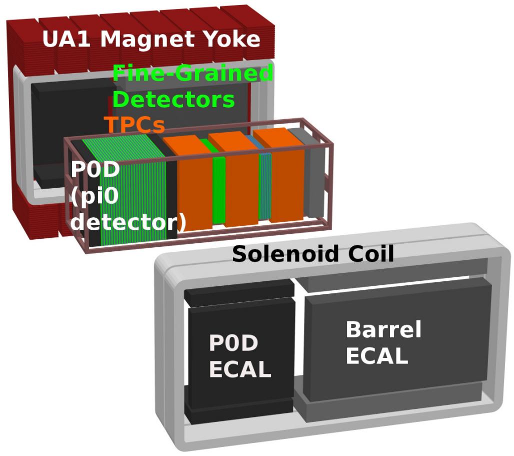

Figure 2: Schematics of ND280 in the opened magnet position. The tracker is visible next to the P0D, with its 3 TPCs and 2 FGDs represented in fake color for display purposes.

measured after oscillation 295 km away from the production target by the 50 kt water Cherenkov detector Super-Kamiokande (SK) [1]. This neutrino beam is detected before oscillating by a first set of detectors located 280 m from the production target called INGRID and ND280. The SK and ND280 detectors are installed in an off-axis configuration, 2.5° away from beam center. This "off-axis" configuration enhances the neutrino oscillation probability by narrowing the neutrino energy distribution around 600 MeV at the oscillation maximum.

INGRID monitors the stability of the neutrino interaction rate and the position of the neutrino beam throughout data taking periods. The INGRID measurement provides a precision better than 1 mrad on the neutrino beam direction. The INGRID apparatus is composed of 16 identical modules made of 11 layers of scintillator bars alternating with 9 iron plates. These layers are surrounded by veto scintillator planes to veto background entering the module from the sides. 14 of these modules are installed in a cross pattern centered on the beam axis with a width of 10 m which corresponds to 1σ of the neutrino beam spatial width (see Fig. 1). Two additional modules are installed off of the main cross to measure the asymmetry of the beam. INGRID also contains an additional module called the proton module and composed entirely of scintillator bars. It is installed in the center of INGRID on the beam axis.

ND280 is a complex of multiple subdetectors installed inside the refurbished magnet from the UA1 experiment, which provides a 0.2 T magnetic field (Fig. 2). The central part of ND280 is the tracker which is composed of two fine-grained detectors (FGDs) [2] and three time projection chambers (TPCs) [3]. 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 and multi-pixel photon counters. 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 active scintillator and inactive 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, CF_4, 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 $(\mathrm{GeV}/c)^{-1}$. 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 π^0 reconstruction and made of scintillator bars interleaved with lead and brass sheets [4]. The tracker and the P0D are surrounded by electromagnetic calorimeters (ECals) composed of layers of plastic scintillator bars with lead sheets in between [5].

3. INGRID cross-section measurements

3.1. ν_μ charged current inclusive event selection

The INGRID analysis identifies the muon from ν_μ charged current (CC) interactions by looking for long tracks originating from the fiducial volume of each module. A 3D track reconstruction algorithm finds the candidate vertex and verifies that it is not in the first scintillator plane of the module. Also the track is extrapolated into the side veto planes of the module and if a hit is found close to the extrapolation, the event is rejected. Finally events with a vertex within ±50 cm from the module central axis, parallel to the beam axis, are selected. The events are also selected in time by imposing that they lie within ±100 ns from the expected timing of the closest beam bunch. This selection has a purity of ν_μ CC interactions above 85%.

3.2. ν_μ CC inclusive cross-section results

The ν_μ CC inclusive selection used to monitor the neutrino beam was also used to calculate flux-averaged ν_μ CC inclusive cross sections. The number of background events N_{BG} and the selection efficiency ϵ_{CC} were extracted from Monte Carlo simulation to correct the number of selected events N_{sel}:

$$\sigma_{CC} = \frac{N_{sel} - N_{BG}}{\Phi T \epsilon_{CC}}, \quad (1)$$

where Φ is the integrated ν_μ flux, and T is the number of target nucleons. Since the standard and the proton modules are composed of respectively 98% iron and 96% hydrocarbon, it is possible to extract two cross-section measurements on two very different sets of nuclei:

$$\sigma^{Fe}_{CC} = (1.444 \pm 0.002(stat.)^{+0.191}_{-0.159}(syst.)) \times 10^{-38}\mathrm{cm}^2/\mathrm{nucleon}, \quad (2)$$

$$\sigma^{CH}_{CC} = (1.379 \pm 0.009(stat.)^{+0.150}_{-0.181}(syst.)) \times 10^{-38}\mathrm{cm}^2/\mathrm{nucleon}. \quad (3)$$

Both measurements are consistent with the predictions from the two neutrino interaction generators used in T2K called NEUT [6] and GENIE [7]. The main systematic uncertainty is from the neutrino flux at about 12%. One major advantage of the INGRID configuration is that the standard and proton modules are exposed to an almost identical flux. Therefore the neutrino flux uncertainty reduces greatly for the cross-section ratio:

$$\sigma^{Fe}_{CC}/\sigma^{CH}_{CC} = 1.047 \pm 0.007(stat.)^{+0.028}_{-0.027}(syst.). \quad (4)$$

This ratio is compared in Fig. 3 to the predictions from the NEUT and GENIE neutrino interaction generators. The integrated cross section is: neutrino event generators and it is is consistent with Monte Carlo simulations.

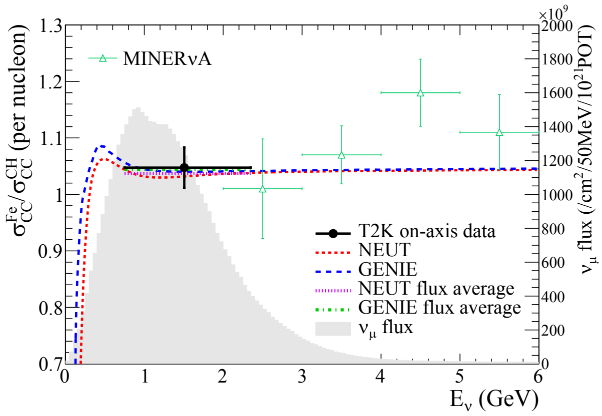

Figure 3: Flux averaged cross section ratio of Fe over CH from the INGRID detector. The horizontal error bar represents 68% of the neutrino flux and the vertical one bar represents the total uncertainty.

3.3. Future measurements

Following the successful ν_μ CC inclusive measurement, other cross-section analyses are underdevelopment. Due to the pion decay kinematics at the production target, the neutrino energy spectrum changes across the 10 m covered by INGRID. It is therefore possible to perform an energy dependent ν_μ CC inclusive measurement by comparing the interaction rate in the different INGRID modules. Two standard modules symmetric to one another with respect to the central module are analyzed together to reduce the effects of the fluctuations of the neutrino beam position.

A second analysis using only the proton module focusses on the charged current quasi-elastic (CCQE) channel in which the neutrino interacts with a neutron of the target and a muon is emitted, sometimes accompanied by a proton. This measurement relies on the NEUT generator's predictions of nuclear effects such as the final state interaction affecting the outgoing particles from an interactions. The cross-section results will serve as validation of the NEUT generator.

4. ND280 measurements

4.1. ν_μ CC inclusive event selection

The analysis of the ND280 data to extract the muon neutrino interaction rate starts by selecting all the ν_μ charged current interactions occurring in the FGD1 detector. In each event, the highest-momentum negative track reconstructed in TPC2 is the muon candidate track. This candidate is required to start from the fiducial volume of FGD1 and be within 60 ns of the closest beam bunch. Events with a track in TPC1, upstream of FGD1, are rejected to reduce background contamination. Finally the candidate tracks with an energy loss in the TPCs compatible with a muon hypothesis are selected as CC inclusive interactions. The muon purity of this selection is ~ 90% and the remaining background is due to the indistinguishable negative pion contamination.

4.2. ν_μ multipion samples

The CC inclusive interaction sample is split into one of three subsamples based on the pion content of the event. If no pion is detected, then the event goes into the CC0pi sample. An event with only one positive pion is classified as a CC1pi event. Finally the CCother sample contains all the events not belonging to the CC0pi and CC1pi samples, which are typically deep inelastic scattering interactions. These subsamples are not defined by neutrino interaction types such as CCQE because the pion emitted from a CC $1\pi^+$ interaction can undergo final state interactions in the nucleus and be reabsorb making it indistinguishable from a CCQE event. For this reason our samples are defined by the number of pions leaving the nucleus rather than the true interaction type.

The pions are identified differently depending if they stopped in FGD1 or if they reached TPC2. For the latter, the energy loss particle identification in the TPC is used to determine if the track corresponds to a pion, and the charge from the track reconstruction separates the positive and negative pions. For pions stopping in FGD1, a particle identification using energy loss can identify a pion if it left a track sufficiently long to be reconstructed. There is no charge identification in this case so all pion-like tracks are assumed to be positive pions. A search for delayed hits in FGD1 is also performed to find the decay of the muon produced by the decay of the positive pion at rest. This decay search does not require a reconstructed track.

This division of the CC inclusive sample provides a separate measurement of the CCQE interactions which dominate the CC0pi sample and are used in SK for the oscillation measurement, and CC1pi interactions which represent a background of the CCQE signal in SK when the pion is not reconstructed in SK. The CC0pi and CCother samples have a purity ~ 73% while the CC1pi is slightly below 50%. This is due to a π^0 contamination in the CC1pi sample which will be addressed in a future analysis by using the ECals to identify these π^0 and move these events to the CCother sample. The three samples are used to constrain the neutrino flux and cross-section systematic uncertainty on the simulation prediction in both the electron neutrino appearance and the muon disappearance measurements in SK.

4.3. ν_μ CC inclusive cross-section results

The cross section is measured from the muon momentum-angle spectrum using:

$$\langle \frac{\partial^2 \sigma}{\partial p_\mu \partial \cos\theta_\mu} \rangle_{kl} = \frac{N^{\rm int}_{kl}}{T \phi \Delta p_{\mu,k} \Delta \cos\theta_{\mu,l}} \quad (5)$$

with $N^{\rm int}_{kl}$ the number of true interactions in the true bin kl, T the number of target nucleons, ϕ the flux, p_μ the muon momentum, and $\cos\theta_\mu$ the angle between the muon direction and the neutrino beam axis. In order to obtain $N^{\rm int}_{kl}$, we unfold the momentum-angle resolution from the measured CC inclusive spectra using an iterative method based on the Bayes' theorem [8]. 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 flux-averaged cross section is compared in Fig. 4 to the NEUT and GENIE predictions. The integrated cross section is:

$$\begin{aligned} \langle \sigma_{\rm CC} \rangle_\phi &= (6.93 \pm 0.13(stat.) \pm 0.85(syst.)) \\ &\quad \times 10^{-39} {\rm cm}^2/{\rm nucleons}. \end{aligned} \quad (6)$$

This result was published last year [9].

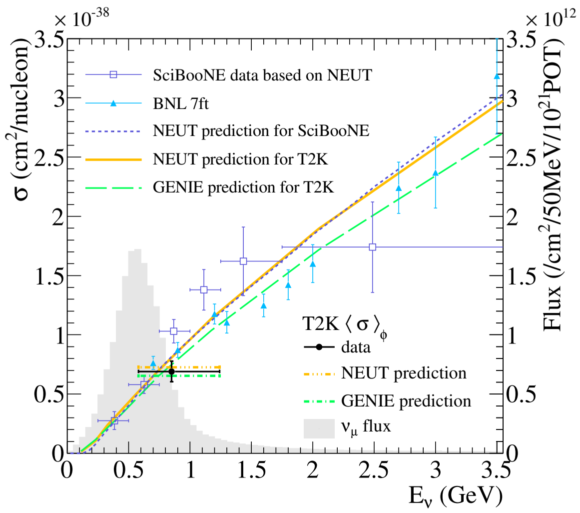

Figure 4: Flux averaged cross section of the ν_μ CC inclusive interaction on carbon. The horizontal error bar represents 68% of the neutrino flux and the vertical one bar represents the total uncertainty.

4.4. ν_e CC event selection

Although the T2K beam is dominated by muon neutrinos a contamination of electron neutrinos is unavoidable and is expected to represent 1.2% of the flux at the off-axis angle. An analysis was developed to measure this contamination in order to confirm the prediction. This is an important verification since this ν_e contamination represents an irreducible background for the electron neutrino appearance measurement.

The first steps of the selection of ν_e CC events are similar to the ν_μ CC inclusive selection, selecting the highest momentum negative track as electron candidate originating from FGD1 and crossing TPC2. TPC particle identification then selects electron-like tracks instead of muon-like tracks. To reject even more muons, the selection also uses the ECals when the electron candidate reaches them. The electron purity of this selection is 92% however only 27% of the tracks actually arise from ν_e CC interactions, because 65% of the selected electrons originate from $\gamma \rightarrow e^+e^-$. Additional selections are applied to reduce this background. The first is a veto on events containing reconstructed tracks originating 100 mm upstream of the electron candidate. And finally the invariant mass is calculated when a positron and an electron are reconstructed in the TPCs. The event is rejected if the invariant mass is below 100 MeV/c^2 to remove electrons from photon conversions. Finally events containing an electron candidate with a momentum below 200 MeV/c are rejected because this region is dominated by background. These cuts reduce the contamination of $\gamma \rightarrow e^+e^-$ from 65% to 30%.

4.5. Electron neutrino component of the T2K beam

Due to the low statistics of ν_e CC inclusive interactions available, the sample is split into two subsamples referred to as the CCQE and CCnonQE samples. This division is much simpler with events containing only one FGD1-TPC2 track allowed into the CCQE samples and all the other events sent to the CCnonQE sample. The main background in the ν_e analysis is estimated using a γ sample containing events with an electron and a positron in the TPCs. A likelihood fit of the ratio $R(\nu_e)$ between data and simulation for these three samples was performed to determine the ν_e contamination in the T2K beam:

$$R(\nu_e) = 1.01 \pm 0.10. \qquad (7)$$

This result show that the prediction of the contamination is consistent with the measured ν_e component, validating the predicted ν_e beam background for the electron neutrino appearance measurement at SK. Further details on the selection and the electron neutrino contamination measurement can be found in [10].

4.6. ν_e CC inclusive cross-section results

The ν_e CC inclusive cross-section measurement uses the same Bayes unfolding technique as the ν_μ CC inclusive results with one difference. The ratio data/simulation of the number of events in the γ sample is used to reweight the background in the ν_e selection. This correction reduces significantly the systematic uncertainties from the cross section of neutrino interaction on heavy nuclei producing neutral pions which are responsible for the γ background.

The total flux averaged ν_e CC inclusive cross section obtained after unfolding is:

$$\langle\sigma_{CC}\rangle_\phi = (1.11 \pm 0.10(stat.) \pm 0.18(syst.)) \times 10^{-38}\text{cm}^2/\text{nucleons}. \qquad (8)$$

This cross-section result is particularly important because it is the first ν_e cross-section measurement at energies $\sim$ 1 GeV since the Gargamelle measurement from 1978. Furthermore this cross section is crucial to future electron neutrino appearance experiments which will search for CP violation. The ND280 flux averaged cross section is consistent with the generator's predictions and also the Gargamelle results (see Fig. 5). This cross-section measurement is presented in more details in [11].

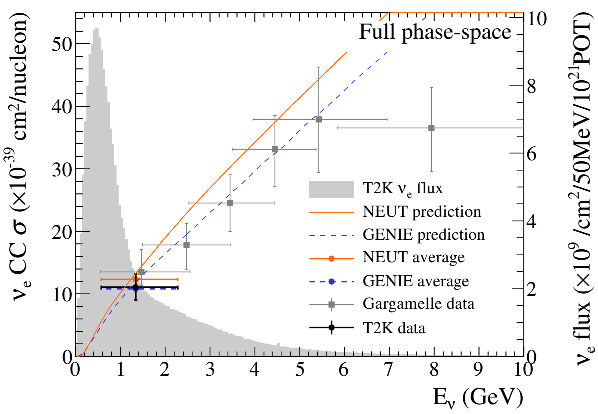

Figure 5: Total ν_e CC inclusive cross section on carbon obtained when unfolding through the four-momentum transfer calculated assuming CCQE interaction kinematic. The horizontal error bar represents 68% of the neutrino flux and the vertical one bar represents the total uncertainty.

4.7. Future measurements

ND280 has now demonstrated that it can provide crucial cross-section measurements for ν_μ and ν_e CC inclusive interactions on carbon. The collaboration is now focusing on the measurements of specific ν_μ charged current channels such as CCQE-like and CC1π interactions rather than updating the CC inclusive measurement. We are also developing the analysis and the systematic uncertainties to exploit FGD2 and its water layers to eventually measure cross sections on water and have better constraints on the interaction rate in the water of SK for the oscillation measurements. The multiple subdetector structure of ND280 allows for very different measurements. The TPCs for example provide a unique environment to study nucleon emission due to the low density of the argon gas at atmospheric pressure. Indeed the low interaction rate means that any cross-section result will be statistically limited however the minimum energy threshold to detect a proton, below 1 MeV kinetic energy, will offer perfect conditions to observe proton multiplicity and momentum. A new reconstruction and analysis are under development to perform the first measurement of a neutrino-gas interaction cross section. The first results are expected in 2015.

So far only neutrino cross sections have been measured in ND280 because T2K has taken data only in neutrino beam mode until recently. However the month of June 2014 was dedicated to taking data in anti-neutrino beam mode, with the focusing horns of the production beamline in opposite polarity. We use the term "the beam mode" rather than the beam itself because the anti-neutrino beam mode contains a significant contamination of muon neutrinos. Furthermore the total anti-neutrino cross section is approximately a factor of 3 lower than the neutrino cross section due to the helicity of the anti-neutrino suppressing the interaction. As a consequence, the ν_μ interaction rate in anti-neutrino beam mode is not negligible and is a main background for $\bar{\nu}_\mu$ oscillation measurements using a far detector that doesn't reconstruct the charge of the outgoing lepton such as the water Cherenkov detector SK. On the other hand ND280 is equipped with a magnet that provides the muon charge and therefore it can discriminate between ν_μ and $\bar{\nu}_\mu$ interactions. Therefore the ND280 measurement of the ν_μ and $\bar{\nu}_\mu$ interaction rates will be even more crucial for the oscillation measurement in anti-neutrino beam mode. Furthermore, there are very few measurements of the $\bar{\nu}_\mu$ cross section below 1 GeV of neutrino energy which means that any cross-section measurement from ND280 will be a useful contribution to the understanding of the anti-neutrino cross sections.

5. Conclusion

The T2K contribution to neutrino physics goes beyond oscillation parameter measurements. Its near detectors have demonstrated strong capabilities in neutrino cross-section measurements which are crucial for the development and validation of theoretical models of neutrino interactions. The multiple components of the near detector apparatus has provided measurements on carbon and iron and will provide results on oxygen and argon. The peak of the neutrino beam energy in ND280 is located around 600 MeV where the CCQE interaction is dominant which will allow ND280 to measure specifically the cross section of this interaction for neutrinos and anti-neutrinos. Along with new data, the calibration and reconstruction software is undergoing significant improvements in particular to increase the angular coverage of the ND280 selections.

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