Selection of electron (anti-)neutrinos at the T2K near detector ND280

G. Christodoulou¹, S. King², B. Jamieson³, P. Lasorak² and N. McCauley¹ on behalf of the T2K collaboration

¹ Department of Physics, University of Liverpool, Liverpool, United Kingdom
² School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom
³ Department of Physics, University of Winnipeg, Winnipeg, Manitoba, Canada

E-mail: Georgios.Christodoulou@liverpool.ac.uk

Abstract. The intrinsic electron neutrino contamination of the T2K neutrino beam provides the single largest background in the measurement of electron neutrino appearance in T2K. These electron neutrinos can be measured directly in the T2K near detector ND280. Measurements of the intrinsic electron (anti-)neutrino backgrounds from the anti-neutrino running are shown, including details on the event selections and rejection of the large background of muons, photons, protons and pions. The $\nu_e$ and $\bar{\nu}_e$ beam compositions are then extracted and the rescaling parameters of the expected rate of $\nu_e$ and $\bar{\nu}_e$ events are $f(\nu_e) = 1.250 \pm 0.135({\text{stats.}}) \pm 0.122({\text{syst.}})$ and $f(\bar{\nu}_e) = 1.142 \pm 0.144({\text{stats.}}) \pm 0.132({\text{syst.}})$ respectively.

1. Introduction
The measurement of the $\nu_\mu \rightarrow \nu_e$ (and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$) oscillation signal, which is the main goal of the T2K experiment [1], is affected by two main background sources. The first is the intrinsic $\nu_e$ and $\bar{\nu}_e$ beam contamination and the second is the NC $\pi^0$ where the $\pi^0$ can mimic the electron signal. The measurement of these two background channels is particularly important and the near detector is crucial to understand them.

The neutrino beam is produced at the J-PARC accelerator complex where a proton beam, accelerated up to 31 GeV/c, is impinged into a graphite target producing hadrons, mainly pions and kaons. The proton beam is extracted in 5.6 $\mu$s long spills and each spill has eight bunches, each 15 ns wide. The charged hadrons produced are focused by three magnetic horns operating at $\pm 250$ kA before entering a 96 m long decay volume where they decay mainly to muon neutrinos. The $\sim 1\%$ electron neutrino beam component is also produced by kaon and muon decays. Kaons can decay to electron neutrinos through the lepton decay channels, $K^\pm \rightarrow \pi^0 + e^\mp + \nu_e(\bar{\nu}_e)$ and $K^0_L \rightarrow \pi^+ + e^- + \nu_e(\bar{\nu}_e)$. Muons are produced from decayed pions and decay to electron neutrinos through $\mu^\pm \rightarrow e^\pm + \bar{\nu}_\mu(\nu_\mu) + \nu_e(\bar{\nu}_e)$. Together these combinations form the $\nu_e$ and $\bar{\nu}_e$ spectrum.

2. The T2K near detector ND280
The T2K off-axis near detector, ND280, is located 280 meters from the neutrino beam and is 2.5 degrees off the neutrino beam center. It is a magnetized detector designed to measure neutrino...
interactions from the T2K beam before neutrino oscillations occur. It is composed of a number of subdetectors installed inside the refurbished UA1/NOMAD magnet, which provides a 0.2 T magnetic field. The tracking detector is composed of two fine-grained detectors (FGD [2]) and three time projection chambers (TPC [3]). The FGDs are used as the target for the neutrino interactions. The upstream FGD (FGD1) is composed solely of scintillator bars, while the downstream FGD (FGD2) contains alternate scintillation-water layers. Upstream of the tracker is the $\pi^0$ detector (P0D [4]). The tracker and P0D are surrounded by the electromagnetic calorimeters (ECal [5]). Finally, the side muon range detector (SMRD [6]) is instrumented inside the magnet yokes to tag high angle muons. More details about the T2K near detector complex can be found in [1].

3. Selection of electron (anti-)neutrino candidates in the ND280 tracker
Electron neutrino candidates are selected from neutrino interactions occurring in the two FGDs. Good beam spill and good ND280 data quality are first applied. In every spill, the reconstructed tracks in each bunch are checked. The highest momentum negative track in each bunch, starting inside the fiducial volume of the FGDs and entering the TPC, is selected. To reduce the large muon, pion and proton backgrounds, electron particle identification (PID) criteria are applied. First, using the TPC dE/dx to calculate the pulls, expressed as the difference between the measured and expected mean ionization divided by the resolution. Then the ECal PID, based on the shower development and its energy deposition in the ECal, is applied. Figure 1 shows the TPC measured dE/dx for negative tracks, the TPC electron pull and the ECal PID. Although a clean sample of electrons is selected, many of the events are coming from photons which produce $e^+e^-$ pairs in the FGDs. This $\gamma$ background is reduced by searching for a positron and applying an invariant mass cut, and vetoing on activity in TPCs, the P0D, and ECals upstream of the FGDs. To constrain the $\gamma$ background, an independent gamma control sample is selected by finding $e^+e^-$ pairs that enter the TPC and have a low invariant mass. Events with $p < 200$ MeV/c are rejected as they are heavily contaminated from background. Details of the charged-current inclusive electron neutrino selection in the neutrino beam can be found in [7].

The selection of electron anti-neutrinos is identical with the selection of electron neutrinos, but selecting the highest momentum track and requiring it to be positive. As is shown on the left plot in Figure 1, a complexity arises in the anti-neutrino selection since the electron and proton TPC dE/dx curves cross around 1 GeV/c. To remove this proton background, additional selection criteria are applied using the ECals and FGD2 to tag electromagnetic showers.

3.1. Electron (anti-)neutrinos in the anti-neutrino beam
The selected electron (anti-)neutrino candidates obtained from the 2014 and 2015 anti-neutrino data, corresponding to $3.67 \times 10^{20}$ good quality protons-on-target (POT), and after applying all
Figure 2. Selected candidates from both FGDs in the $\nu_e$ (left) and $\bar{\nu}_e$ (right) selection in the anti-neutrino beam.

The selection criteria are shown in Figure 2. The efficiency for the $\nu_e$ selection is 37% and the purity is 53%, while the efficiency for the $\bar{\nu}_e$ selection is 37% and the purity is 62%.

The $\nu_e$ and $\bar{\nu}_e$ beam compositions are then extracted from a simultaneous maximum likelihood fit on the three samples; $\nu_e$, $\bar{\nu}_e$ and the gamma control sample. The best fit results for the rescaling parameters of the expected rate of $\nu_e$ and $\bar{\nu}_e$ events are $f(\nu_e) = 1.250 \pm 0.135(\text{stats.}) + 0.122(\text{syst.})$ and $f(\bar{\nu}_e) = 1.142 \pm 0.144(\text{stats.}) + 0.132(\text{syst.})$ respectively. Both rescaling parameters are fitted above their nominal value of one, but much of the excess observed is coming from the high energy tail of the momentum spectra. Analysis of the 2016 anti-neutrino data is currently ongoing and will provide a significant push in the statistics for both $\nu_e$ and $\bar{\nu}_e$ selections and in the estimation of the electron (anti-)neutrino beam component.

4. Conclusions and future plans

The intrinsic electron (anti-)neutrino contamination of the T2K neutrino beam can be directly measured in the T2K near detector which is important to constrain the irreducible electron (anti-)neutrino background in the measurement of electron (anti-)neutrino appearance at the far detector. In addition, these samples can provide unique electron (anti-)neutrino cross-section measurements which are very important, not only for T2K, but, also for the future long baseline neutrino oscillation experiments. The charged-current (CC) inclusive electron neutrino cross section in the neutrino beam has been measured in Ref. Furthermore, a dedicated electron neutrino CC-0$\pi$ selection has been developed, requiring that the selected electron neutrino candidate is not accompanied by any pion-like tracks. With more anti-neutrino data taken in 2016, it is in the future plans to also measure the CC inclusive electron anti-neutrino cross section.

References
[1] K. Abe et al. (T2K Collaboration), Nucl. Instrum. Methods A659, 106 (2011).
[2] P. Amaudruz et al. (T2K ND280 FGD Collaboration), Nucl. Instrum. Methods A696, 1 (2012).
[3] N. Abgrall et al. (T2K ND280 TPC Collaboration), Nucl. Instrum. Methods A637, 25 (2011).
[4] S. Assylbekov et al. (T2K ND280 P0D Collaboration), Nucl. Instrum. Methods A686, 48 (2012).
[5] D. Allan et al. (T2K UK Collaboration), JINST 8, P10019 (2013).
[6] S. Aoki et al. (T2K ND280 SMRD Collaboration), Nucl. Instrum. Methods A698, 135 (2013).
[7] K. Abe et al. (T2K Collaboration), Phys. Rev. D 89, 092003 (2014).
[8] K. Abe et al. (T2K Collaboration), Phys. Rev. Lett. 113, 241803 (2014).