Study of neutrino interactions at the T2K near detector

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Abstract. The Tokai to Kamioka experiment (T2K) is a long baseline neutrino accelerator operating in Japan and designed to measure electron neutrino appearance and muon neutrino disappearance. Three gaseous TPCs compose its near detector complex. The latest T2K analysis combines the results from the appearance and disappearance channels to extract simultaneously four neutrino oscillation parameters. Improvements to the TPC field distortion correction are under development to reduce systematic uncertainties for future oscillation analyses. In parallel a cross section measurement of neutrino-gas interactions happening in the T2K TPCs is in preparation in particular to extract unique proton multiplicity and kinematic information.

1. Introduction
Neutrino physics quite an exciting field since the discovery of neutrino flavor oscillations 20 years ago. Measuring and understanding these oscillations is already an interesting topic by itself but the flavor oscillations imply that the mass eigenstates and flavor eigenstates are different. This is in contradiction with the Standard Model (SM) which was built on the assumption that neutrinos are massless therefore we have first hints of physics beyond the SM. Furthermore, CP symmetry could be violated by neutrino oscillation. A confirmed CP violation in the neutrino sector would open the possibility of using leptogenesis to explain the matter-antimatter in the Universe.

This has motivated the measurement of the mixing angles $\theta_{12}$, $\theta_{13}$, and $\theta_{23}$ defining the mixing of the three mass states as well as the difference $\Delta m^2_{21}$ and $\Delta m^2_{32}$ between the mass states. The discovery of a relatively large value of $\theta_{13}$ has started the era of precision measurements of these parameters. Precision measurements will require a reduction of the neutrino cross section systematic uncertainties and therefore a better understanding of the neutrino-nucleus interactions.

The Tokai to Kamioka (T2K) experiment started operating when $\theta_{13}$ had only an upper limit set from previous experiments. T2K was designed to measure $\theta_{23}$ and $\Delta m^2_{32}$ from muon neutrino disappearance and $\theta_{13}$ from electron neutrino appearance. The collaboration made the unique choice in accelerator neutrino experiments to use three gaseous TPC in its near detector to reconstruct the momentum and the charge of the particles produced by neutrino interactions. This paper will present the latest T2K results and some overview of work done to understand electric field distortions in the T2K TPCs. The prospects of the first ever analysis of interactions between neutrinos and a gas inside the T2K TPCs will be also presented.
Figure 1. The ND280 schematic shows the tracker with its 3 TPCs and 2 FGDs represented in fake color for display purposes. The walls of the inner box are visible in this TPC cutaway.

2. The apparatus

In T2K, a beam of muon neutrinos is produced at the J-PARC facility in Tokai, Ibaraki, Japan, and it is measured after oscillation 295 km away from the production target by the 50 kT water Cherenkov detector Super-Kamiokande (SK) [1]. T2K was the first accelerator neutrino experiment to adopt an “off-axis” configuration by positioning SK 2.5° away from the beam center. This configuration enhances the neutrino oscillation probability by narrowing the neutrino energy distribution around 600 MeV at the oscillation maximum. The near detector ND280 located 280 m from the production target is also installed “off-axis” and measures the neutrino interaction rate before the oscillation to constrain beam and cross section systematic uncertainties.

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. 1(a)). The central part of ND280 is the tracker which is composed of two fine-grained detectors (FGDs) [3] and three time projection chambers (TPCs) [2]. The FGDs are composed of alternating vertical and horizontal layers of 1 cm² 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 T2K TPCs are composed of an inner box used for the tracking and an outer box fill with CO₂ for electric insulation of the inner box (Fig. 2(b)). Each inner box is filled with an argon, CF₄, and isobutane gas mixture at respectively 95, 3, and 2% and uses MicroMegas detectors (MMs) for gas amplification with pad readout. A central cathode splits each TPC into two drift volumes, each equipped with 12 MMs composed of 36 × 48 pads with a size of 9.8mm × 7.0mm and an amplification gap of 128 µm. The readout electronic is based on ASIC chips with 72 channels and operating at 25 MHz. 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 $\pi^0$ 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. T2K recent results
Before even collecting 10% of its targeted total amount of data, T2K has achieved significant milestones in its scientific program. T2K has performed the first conclusive observation of a neutrino flavour appearance by measuring the appearance of electron neutrinos in SK in the J-Parc muon neutrino beam with a significance of 7.3\sigma [6]. T2K also produced some of the most precise measurements of the $\sin^2 \theta_{23}$ and $\Delta m_{32}^2$ parameters from its muon neutrino disappearance analysis [7]. However a combine analysis of T2K’s appearance and disappearance channels has become necessary in order to fully extract the four oscillation parameters that T2K is sensitive to: $\sin^2 \theta_{23}$, $\Delta m_{32}^2$, $\sin^2 \theta_{13}$, and $\delta_{CP}$. Indeed with the increased precision of the appearance and disappearance analyses, the dependence on more than one mixing angle of the oscillation probabilities cannot be ignored anymore. More precisely looking at the leading terms for the electron neutrino appearance and muon neutrino disappearance:

$$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2 \theta_{23} \cdot \sin^2 2\theta_{13} \cdot \sin^2 \left(\frac{\Delta m_{32}^2 L}{4E_\nu} \right)$$

$$P(\nu_\mu \rightarrow \nu_e) \approx 1 - (\cos^4 \theta_{13} \cdot \sin^2 2\theta_{23} + \sin^2 \theta_{23} \cdot \sin^2 2\theta_{13}) \sin^2 \left(\frac{\Delta m_{32}^2 L}{4E_\nu} \right)$$

one sees that both $\theta_{13}$ and $\theta_{23}$ have a significant impact. Furthermore T2K is not currently capable of separating the contribution from $\theta_{13}$ and the CP violation $\delta_{CP}$. The reactor neutrino measurement of $\sin^2 2\theta_{13}$ on the other hand is insensitive to $\delta_{CP}$ and can be therefore used to break the degeneracy between $\theta_{13}$ and $\delta_{CP}$ in the T2K data.

One of the approaches used by the T2K collaboration to combine its appearance and disappearance channels as well as the reactor neutrino experiment results on $\sin^2 2\theta_{13}$ was to perform a Bayesian inference analysis to construct posterior probability distributions for the four parameters and marginalize over all the systematic uncertainty parameters. In this approach the knowledge of the neutrino beam and neutrino cross sections as well as the reactor neutrino experiment results is included in the form of prior probability distributions. The ND280 detector measurement of the muon neutrino interaction rate prior to oscillation provides constraints on the neutrino beam and cross section parameters. The prior information, ND280 events and SK events are combined in a likelihood function to create the posterior distribution using a Markov Chain Monte Carlo since it cannot be computed analytically. The credible regions for $\delta_{CP}$ with respect to $\sin^2 \theta_{13}$ show how the reactor neutrino results break the degeneracy between the two parameters (see Fig. 2(a)). The probability density for $\delta_{CP}$ after marginalization over all the other parameters shows a preference of the results for $\delta_{CP} \approx -0.5\pi$, however the credible interval at 90% extends to $\delta_{CP} = 0$ therefore this preference is not significant. Nonetheless these results demonstrate T2K’s capacity to contribute to the neutrino community search for the value of $\delta_{CP}$.

In May 2014 T2K has started collecting data with its beamline set in anti-neutrino beam mode. In this mode the ND280 detector, and in particular the charge measurement from its TPCs, will be essential to the oscillation measurement since the muon neutrino interaction rate in anti-neutrino beam mode is non negligible compared to the anti-muon neutrino and SK does not reconstruct the charge the charged leptons. The anti-muon neutrino disappearance and anti-electron neutrino appearance will provide crucial information for the $\delta_{CP}$ search and pave the way to a future discovery of this parameter by the next generation of long baseline neutrino experiments.
4. Studies of the TPC electric and magnetic fields

The T2K TPCs play a central role in the ND280 analysis and therefore in the T2K oscillation results. For this reason the TPC calibration and reconstruction are always being developed and improved to try to reduce the systematic uncertainties relative to the TPC tracking. For example the reconstruction of vertical tracks was significantly improved in the latest version of the reconstruction software providing long vertical tracks from cosmic rays subsequently used to improve the gain calibration of the MicroMega detectors. This calibration is essential for the particle identification using the measured energy loss to identify muon tracks and select muon neutrino charge current interactions in the ND280 tracker.

Similarly a lot of work is dedicated to understanding the electric and magnetic fields in the TPCs. In ND280 the electric and magnetic fields are parallel to one another and perpendicular to the neutrino beam direction. The magnetic field was mapped prior to the installation of the detectors inside the ND280 magnet by a high precision mapping apparatus capable of reproducing the position of the magnetic probes with a precision of 10 $\mu$m. The resulting magnetic field map is used in the reconstruction of the data events to correct the displacement of the drift electrons due to the magnetic field distortions. A comparison of the momenta reconstructed in TPC2 and TPC3 from a single particle are used to verify the quality of the correction since TPC2 is near the center of ND280 where the field is very homogeneous while TPC3 is at the edge where significant field distortions are present. Applying the magnetic field correction brings the difference between the two reconstructed momenta from about 6% to less than 2% which is the target for the momentum bias.

The TPCs are also equipped of a laser system at 266 nm which illuminates aluminium dots located on the cathode foil in the middle of each TPC in order to create photo-electrons. The measured position of each dot is compared to the expected position in order to extract the integrated displacements undergone by the photo-electrons as they drifted from the cathode to the readout plane.

Finally the last tool at our disposition is looking at the residuals of a control sample of reconstructed tracks. The advantage of this technique is to be able to probe different parts of the TPC drift volume. Using this technique we have discovered the presence of electric field distortions of identical shape and slightly different amplitude in the six drift volumes. This simple empirical 2D model for the electric potential is capable of reproducing the overall features

Figure 2. Credible intervals for the $\delta$CP parameters versus $\sin^2 \theta_{13}$ and on the $\delta$CP probability density. The other oscillation and systematic uncertainty parameters are marginalized over.
Figure 3. Z component (parallel to the neutrino beam direction) of the electric field distortions.

of the residuals observed in the data:

\[ \varphi(x, z) = A \left[ \sin \left( \frac{2\pi L x}{L} \right) \cosh \left( \frac{z}{b_1} \right) + c \sin \left( \frac{6\pi L x}{L} \right) \cosh \left( \frac{z}{b_2} \right) \right] \]

where \( x \) is along the drift direction, \( z \) is aligned to the neutrino beam, \( L \) is the maximum drift distance and \( A, b_1, b_2, \) and \( c \) are parameters tuned to the data. As shown on Fig. ??, the distortion displays a symmetric structure. The symmetry along the \( x \) axis means that electrons drifting from the cathode are displaced first towards positive (negative) \( y \) and then towards negative (positive) \( y \) but the same amount. As a consequence the integrated displacement observed using the photo-electrons from the laser system is insensitive to these electric field distortions. We are currently improving the empirical model and in parallel we are investigating the possible sources of this electric field distortion using the modeling software COMSOL in order to simulate the TPC electric field. Various deformations of the TPCs such as a bulging of the TPCs walls were tested however the corresponding electric field distortion cannot reproduce our observations in the data.

5. TPC gas interaction analysis

Besides its successes with oscillation measurements, T2K has also provided the neutrino community with multiple cross section measurements. Most of these results were produced using the near detectors and in particular the ND280 tracker for results such as the first electron neutrino cross section measurement at a few GeV energy since the Gargamelle measurement in 1976 [8]. Even a neutral-current interaction cross section on oxygen was performed by observing nuclear deexcitation \( \gamma \) rays in SK [9].

Of all the possible cross section measurement in T2K, the most unique is the possibility to use the T2K TPCs to measure neutrino-argon cross section interaction in a gas phase. Indeed the
T2K TPCs are currently the only gaseous TPCs exposed to an accelerator neutrino. Although the low interaction rate with the TPC gas at 1 atm will lead to statistically limited measurements, any results will be very useful to the neutrino community all the charged particles exiting the nucleus after the neutrino interactions should be detectable, even protons of very low energy. These protons are particularly useful to understand the nuclear effects involved in the neutrino interactions on heavy nuclei.

As a neutrino interacts with a nucleus, it does not always interact with a single neutron to produce a lepton and a proton. Some interactions involve neutrons in a bound state inside the nucleus leading to the emission of additional nucleons and/or pions. Hadronic models are being developed to describe these interactions because they modify the overall neutrino cross section on the nucleus significantly. For example these nuclear effects can explain the apparent discrepancy in the quasi-elastic cross section measurements on carbon from the MiniBooNE and NOMAD experiments [10]. The final state interactions (FSI) on the nucleons complicate the study of the hadronic effects by scattering or absorbing the pions and protons as they exit the nucleus.

Understanding these nuclear effects is very important T2K but also for future long baseline neutrino experiments such as LBNF or LBNO. Both experiments plan to use liquid argon TPCs as their far detector which is why many liquid argon TPC experiments are in preparation or operating already as R&D projects. Some of these experiments, such as ArgoNeuT and MicroBooNE have performed or will perform neutrino-argon cross section measurements to help develop neutrino interaction models. A cross section result from the T2K TPCs would be very complementary to the liquid argon effort because the T2K TPC gas is composed at 95% of argon and it is at a neutrino energy regime where charged current quasi elastic interactions dominate. The ArgoNeuT experiment reported a minimum detection threshold for protons at about 200 MeV/c [11] while we expect to reach 30 MeV/c with the T2K TPCs. The interval below 200 MeV/c covered by the T2K TPCs is particularly interesting because it is expected to be dominated by protons having undergone FSI. Furthermore this interval also displays large discrepancies in the predicted momentum distributions from the NEUT [12] and GENIE [13] neutrino interaction generators as shown on Fig. 3.

Currently the biggest task to develop the neutrino-gas interaction analysis in T2K TPC is the implementation of a new TPC reconstruction. Indeed although a reconstruction algorithm exists and has been used to produce the published T2K results, it was designed to reconstruct tracks from particles originating from outside the TPCs. This is why a new reconstruction code called TREx for TPC reconstruction extension was written and is currently undergoing validation. TREx was designed with the concept of vertex connecting multiple tracks and can therefore identify and handle the gas interaction vertices inside the TPCs. Components from the previous TPC reconstruction were reused such as the maximum likelihood fit of the tracks providing a bias and a resolution respectively below 2% and 10% at 1 GeV/c. The challenge of the reconstruction and the analysis will be to discern the signal from the large background of tracks originating from the detectors surrounding the TPCs and in particular from the lead of the ECals. The first neutrino-gas interaction results are expected in 2015.

6. Conclusion
By performing a combined analysis of its neutrino electron appearance and neutrino muon disappearance data, T2K has demonstrated its capacity to provide in the future, given more data, the first hints of the CP phase. To guarantee that future measurements are not systematics limited, ongoing work is dedicated to understanding the source of the TPCs electric field distortions that were discovered recently. Improvements to the TPC reconstruction are also underway to allow the reconstruction of neutrino interactions happening inside the TPC themselves and perform very promising measurements of these interactions and their byproducts.
Figure 4. Neutrino generator prediction for the momentum distribution of all the protons emitted from neutrino interactions on argon.

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