Status of the T2K experiment

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T2K is a long baseline (295 km) neutrino oscillation experiment. A 30-GeV proton beam at J-PARC produces a muon neutrino beam aimed at the near detector complex and the far Super-Kamiokande detector. The goal of T2K is the search for $\nu_\mu \to \nu_e$ oscillations. This article describes the status of T2K in the first year of operation. In 2009, the beamline was commissioned and all the components worked as expected. In 2010, T2K neutrino events have been detected and T2K has started searching for the electron neutrino appearance.

1 Introduction

The phenomenon of neutrino oscillations, where neutrinos change from one flavor to another during propagation in vacuum or matter, is well established. This implies that neutrinos have masses and that leptons mix. Neutrino flavor eigenstates $|\nu_\alpha\rangle$ ($\alpha = e, \mu, \tau$) are written as linear combinations of mass eigenstates $|\nu_i\rangle$ ($i = 1, 2, 3$) using a 3×3 unitary mixing matrix U as $|\nu_\alpha\rangle = \sum_{i=1}^{3} U_{\alpha i} |\nu_i\rangle$. This matrix is referred to as the MNS (Maki-Nakagawa-Sakata) matrix [1]. In this picture, neutrino oscillations can be described by six parameters: two independent mass-squared differences $\Delta m^2_{ij} \equiv |m^2_i - m^2_j|$ (Δm^2_{12}, Δm^2_{23}), three mixing angles θ_{ij} ($i, j = 1, 2, 3$; $i \neq j$) and a CP-violating phase δ. The matrix U can be written as a product of three rotations:

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}, \quad (1)$$

where $c_{ij} \equiv \cos\theta_{ij}$ and $s_{ij} \equiv \sin\theta_{ij}$.

The evidence of neutrino oscillations was first reported by the Super-Kamiokande (Super-K) experiment which measured a zenith angle dependent deficit of atmospheric muon neutrinos [2]. The K2K experiment confirmed neutrino oscillations by using accelerator-produced neutrinos [3]. Many experiments have measured θ_{12}, θ_{23}, Δm^2_{12} and Δm^2_{23}:

- θ_{12} and Δm^2_{12} by solar [4, 5] and reactor [6] neutrino experiments, yielding $\tan^2\theta_{12} = 0.47^{+0.06}_{-0.05}$ and $\Delta m^2_{12} = 7.59^{+0.21}_{-0.21} \times 10^{-5}$ eV^2;
- θ_{23} and Δm^2_{23} by atmospheric [7-12] and accelerator [13, 14] neutrino experiments, yielding $0.37 < \sin^2\theta_{23} < 0.65$ [a] at 90% C.L. (confidence level) by Super-K [11] and $\Delta m^2_{23} = (2.43 \pm 0.13) \times 10^{-3}$ eV^2 at 68% C.L. by MINOS [14].

However neither θ_{13} nor δ have ever been measured. The current best limit on θ_{13} is from the CHOOZ reactor neutrino experiment [15], which implies $\sin^2 2\theta_{13} < 0.15$ at 90% C.L. for $\Delta m^2_{23} = 2.43 \times 10^{-3}$ eV^2.

The aim of the T2K (Tokai-to-Kamioka) experiment is to measure $\sin^2 2\theta_{23}$ and Δm^2_{23} with a precision of $\delta(\sin^2 2\theta_{23}) \approx 0.01$ and $\delta(\Delta m^2_{23}) < 10^{-4}$ eV^2, respectively, and to probe $\sin^2 2\theta_{13}$ with sensitivity down to 0.006 at 90% C.L. for $\Delta m^2_{23} = 2.4 \times 10^{-3}$ eV^2 assuming $\delta = 0$, normal mass hierarchy, 8×10^{21} 30-GeV-POT (protons on target) and 10% systematic error.

[a] Three flavor oscillation analysis in the assumption of normal mass hierarchy.

2 Strategy of the experiment

The neutrino transition and survival probabilities in vacuum are expressed as:

$$P(\nu_\mu \to \nu_e) \approx \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2 \left(\frac{\Delta m^2_{23} L}{4E_\nu}\right), \tag{2}$$

$$P(\nu_\mu \to \nu_\mu) \approx 1 - \sin^2 2\theta_{23} \sin^2 \left(\frac{\Delta m^2_{23} L}{4E_\nu}\right), \tag{3}$$

where L is the neutrino travel length and E_ν is the neutrino energy. Therefore, the parameters θ_{13}, θ_{23} and Δm^2_{23} can be derived from measurements of the probability as a function of L/E_ν.

In T2K, an almost pure muon neutrino beam is produced by using the 30-GeV proton beam at J-PARC (Japan Proton Accelerator Research Complex) and an energy spectrum of the neutrinos for each flavor (N^{obs}) is measured by the Super-K water Cherenkov detector, 295 km away from J-PARC. An energy spectrum of the neutrinos before oscillation is measured by the near detector (ND280), which is located at the J-PARC site, 285 m downstream of the proton interaction target. In order to predict a spectrum at Super-K in case of null oscillation (N^{null}), the energy spectrum measured by ND280 is extrapolated to Super-K by means of Monte Carlo simulation. For validation and tuning of hadron production models in the Monte Carlo simulation, input is provided by the CERN NA61 hadron production experiment [16]. N^{obs}/N^{null} gives the oscillation probability P as a function of E_ν.

Charged current quasi-elastic CCQE events ($\nu + n \to lepton + p$) are selected to measure the neutrino energy, which is reconstructed from the lepton momentum and angle with respect to the beam direction. Charged current neutrino cross sections scaled to E_ν can be seen in the reference [17]. Non-CCQE events can be a background if they are misidentified as CCQE. The cross section of non-CCQE events increases as a function of neutrino energy while that of CCQE events flattens above a few GeV. Therefore, a sub-GeV neutrino beam is required for T2K to enhance CCQE events.

One of the interesting features of T2K is the off-axis beam configuration: The neutrino beam is aimed at a direction away from Super-K by 2.5 degrees. This configuration makes a neutrino energy spectrum at Super-K more peaked than one in a conventional on-axis beam configuration and the peak energy depends on the off-axis angle. By selecting the off-axis angle at 2.5 degrees, the peak of the spectrum is selected to be around 0.6 GeV where the neutrino oscillation probability is maximum for the 295-km distance. In addition, the number of high energy neutrinos is significantly reduced, resulting in a decrease in background events. In the off-axis configuration, it is important to monitor and tune the neutrino beam direction precisely since the peak energy is a sensitive function of the beam direction. A tolerable shift of the beam direction is < 1 mrad which corresponds to a shift in the peak energy by about 15 MeV.

Another feature of T2K is the expected high statistics due to the intense proton beam at J-PARC (up to 750-kW) along with the large volume (50 kt) of the Super-K detector. With 8×10^{21} POT, the expected number of ν_e appearance events in Super-K ($0.35 \le E_\nu \le 0.85$ GeV) is 143 (14) if $\sin^2 2\theta_{13} = 0.1$ (0.01), while the expected number of background events is 26, of which 16 background events come from intrinsic ν_e in the beam. The ν_e flux contamination is estimated at $\nu_e/\nu_\mu \approx 0.4\%$ at the spectrum peak energy. The rest comes from misreconstructed neutral current (NC) π^0 interactions, which higher energy neutrinos are more likely to cause (see Sec. 3.3).

3 Experimental setup

3.1 The neutrino beam line

A train of six bunches of protons from the J-PARC main ring is extracted as a spill to the neutrino beamline and a spill occurs every 3.5 seconds. It is transported to the graphite target through the

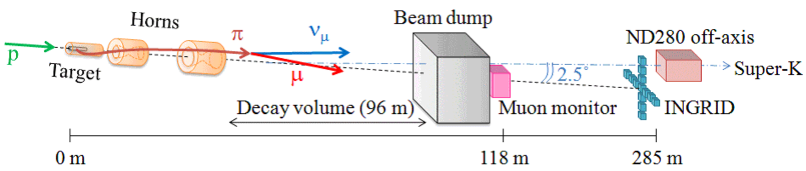

Figure 1: Schematic side view of the T2K neutrino beam line and the near neutrino detectors. An example trajectory of a pion decaying into a muon and a muon neutrino is also drawn.

preparation (∼50 m long), arc (∼150 m) and final focusing (∼40 m) sections. In the preparation section, the extracted proton beam is tuned with a series of normal conducting magnets so that the beam position and size can be accepted by the arc section. The arc section consists of 14 doublets of superconducting combined function magnets [18], which bend the beam by about 80 degrees toward the direction of Super-K. In the final focusing section, normal conducting magnets guide and focus the beam onto the target, while directing the beam slightly downward. The intensity, position, profile and loss of the proton beam in those sections are monitored by five current transformers (CT), 21 electro-static monitors (ESM), 19 segmented secondary emission monitors (SSEM), an optical transition radiation monitor (OTR) and 50 beam loss monitors (BLM).

Figure 1 is a schematic side view of the beamline downstream of the target and the near neutrino detectors. The proton beam impinges on the target to produce pions. The pions are focused by three magnetic horns excited by a 250-kA (to be increased to 320-kA) current pulse and enter the decay volume to decay mainly into muons and muon neutrinos. All the remnants of the undecayed pions and other hadrons are stopped by the beam dump which is made of graphite and iron. Just downstream of the beam dump, the flux and direction of the intense muon beam from the pion decays are measured by the muon monitor [19], which consists of two independent arrays of 49 silicon PIN photodiodes and 49 ionization chambers. The muon beam direction is measured as the direction from the target to the profile center reconstructed by the muon monitor. It should be the same as the neutrino beam direction since both muons and neutrinos originate from the same parent pions. A tolerable shift of the profile center is less than 11.8 cm which corresponds to a 1-mrad shift of the beam direction. To keep the shift less than 1 mrad, the profile center has to be monitored with a precision much better than 11.8 cm. Actually, the muon monitor requirement is even more stringent, and the profile center should be measured with a precision better than 3 cm.

The neutrino beam is measured by the on-axis INGRID (Interactive Neutrino GRID) detector to monitor the beam flux and direction, and by the ND280 off-axis detector to measure neutrino energy spectra, ν_e contamination in the beam, and neutrino interaction cross sections.

3.2 The near detector

ND280 consists of the on-axis detector (INGRID) and the off-axis detector. INGRID consists of seven vertical and seven horizontal modules. Each module is made of iron and segmented plastic scintillator planes. INGRID counts neutrino charged current events in each module to reconstruct the neutrino beam profile. A tolerable shift of the profile center is less than 28.5 cm and the aimed precision of the INGRID measurement is 5 cm.

The off-axis detector [20] consists of several sub-detectors: two fine grain detectors (FGD) to provide active targets for neutrino interactions and to measure the interaction vertices, three time projection chambers (TPC) to measure muon momentum for E_ν reconstruction and dE/dx for particle identification, side muon range detectors (SMRD), a π^0 detector (P0D) to measure NC π^0 production rate and electromagnetic calorimeters (ECAL). The UA1 dipole magnet surrounds the sub-detectors, operating in a 0.2-T magnetic field.

3.3 The Super-Kamiokande detector

Super-K [21] is a 22.5-kt fiducial mass ring-imaging water Cherenkov detector located at a depth of 2,700-m water equivalent in the Kamioka mine. The detector is optically separated into two concentric cylindrical regions: the inner detector instrumented with 11,129 20-inch photomultiplier tubes (PMT) and the outer detector with 1,885 8-inch PMTs. A new high-speed readout electronics system [22] was installed and a new run time called Super-Kamiokande IV started in September, 2008. Synchronization with the J-PARC beam timing is achieved by means of a GPS system.

Super-K has good capability of identifying muons and electrons by analyzing the sharpness of a Cherenkov ring edge. A muon makes a sharp edge ring and an electron makes a fuzzy one due to electromagnetic showers. The probability of misidentification, where a muon is identified as an electron, and vice versa, is about 1% for the T2K neutrino energy. Therefore, ν_e signals can be clearly seen by selecting one-ring electron-like events in CCQE samples. Backgrounds come from the beam ν_e contamination and misreconstructed NC π^0 events ($\nu_\mu + N \rightarrow \nu_\mu + \pi^0 + N'$). The π^0 can be identified by two electron-like rings from its decay into two photons. However, if one of the photons is missed, the event looks same as a ν_e signal.

4 Results from the beam operation

4.1 Beamline commissioning

The neutrino beamline commissioning started in April, 2009. The proton beam orbit was tuned by using the proton beam monitors. Figure 2 shows a sample of the orbit after the extraction from the main ring from December, 2009. The deviation from the ideal orbit was within ± 1 mm in the horizontal and ± 2 mm in the vertical directions.

Muon profiles measured by the muon monitor for 320-kA and 0-kA horn current are shown in Fig. 3. With the horn focusing, the profile narrowed and the peak flux increased by a factor of seven. The muon monitor worked stably; fluctuation of the flux and direction measurement during continuous operation for half an hour was less than 1% in RMS/mean and a few mm in RMS, respectively. The muon profile center was on the beam axis. That means the muon beam direction was well tuned within 1 mrad. When the proton beam hit off-center on the target, the deviation was found by the muon monitor with magnification a few tens of times. Therefore, the muon monitor can also monitor the proton beam shift on the target.

After the successful commissioning of the beamline, continuous beam operations for the ν_e appearance search started in 2010 with all three horns excited by 250-kA current. The beam power increased to 30 kW by March, 2010.

4.2 Neutrino events

The first neutrino event candidate occurred in an INGRID module in November, 2009, and is shown in Fig. 4. The neutrino interaction occurred in the sixth iron plane, and a muon-like long track and a pion or proton-like short track were observed.

Figure 5 shows an off-axis neutrino event in the off-axis detector observed in February, 2010. The neutrino interaction occurred in the P0D and multiple particles were generated. One of them left its track in the TPCs, FGDs and the downstream ECAL (DSECAL). The ND280 off-axis detector successfully started beam data taking with almost full setup [b] in 2010.

[b] Some ECALs in the barrel will be installed during the summer shutdown in 2010.

Figure 6 shows the first candidate of T2K neutrino events inside the fiducial volume of Super-K taken on February 24, 2010. There were three Cherenkov rings and they were fully contained in the inner detector. The first and second rings were showering and their invariant mass was reconstructed to be 133.8 MeV/c^2. Therefore, they are most likely photons from a π^0.

5 Summary

T2K entered a phase of beam data taking in April, 2009. The commissioning of the beamline was successful, and subsequently T2K started ν_e appearance search in 2010. Both ND280 and Super-K are running, all the components are working as expected, and neutrino events are being detected. The first physics result is expected shortly.

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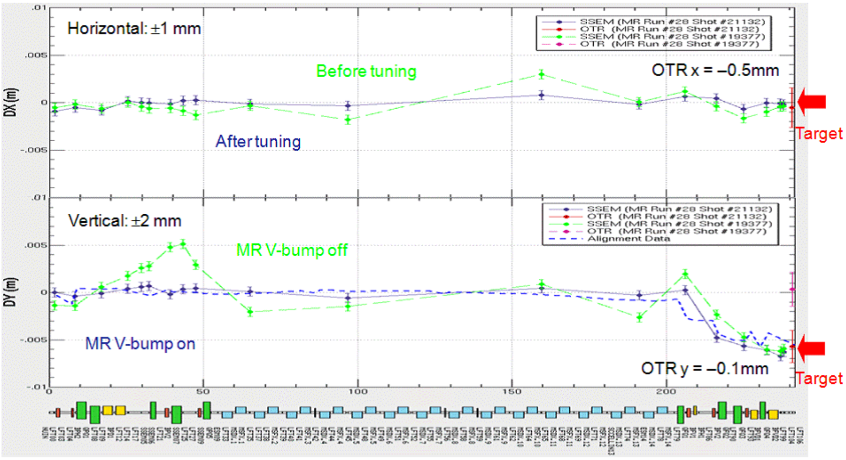

Figure 2: Horizontal (top) and vertical (bottom) proton beam orbits from the extraction point to the target before (green long-dashed lines) and after (blue solid lines) the tuning. The profile centers of the beam were measured by SSEMs and by OTR at the target. The blue broken line in the bottom figure shows the alignment data; The vertical beam orbit should run along the line, while the horizontal one should be zero.

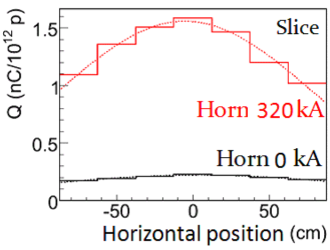

Figure 3: Horizontal profiles measured by the muon monitor silicon PIN photodiodes in the center row for 320-kA and 0-kA horn current. Each histogram is fitted with a Gaussian function (dotted line).

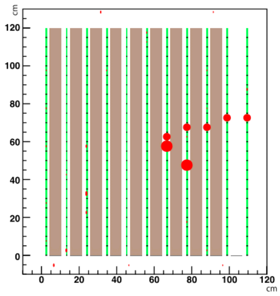

Figure 4: Event display (side view) of an INGRID module showing a neutrino event candidate. The neutrino beam enters from the left side. Looking from upstream, scintillator and iron planes alternate. Red circles on the scintillator planes indicate hits. An amount of energy deposition is represented by area of the circle.

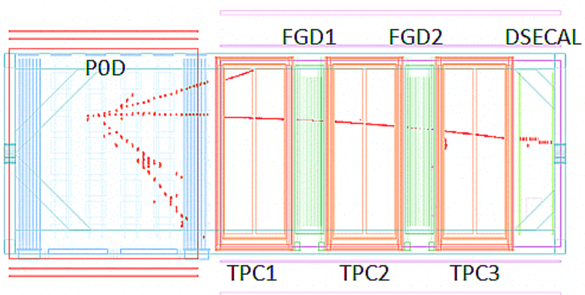

Figure 5: Event display (side view) of the ND280 off-axis detector where a neutrino event occurred in the P0D. The neutrino beam enters from the left side. Red dots show tracks of the daughter particles.

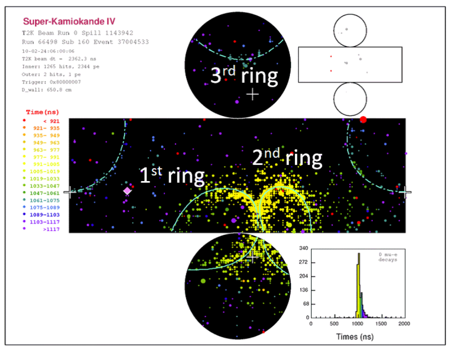

Figure 6: Super-K event display showing the first candidate of T2K neutrino events. Dots in the detectors shows PMT hits. There are three Cherenkov rings with fitted circles.