THE T2K EXPERIMENT: FIRST RESULTS AND FUTURE PLANS*

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T2K is the first off-axis long-baseline neutrino oscillation experiment. It aims at the measurement of the θ_{13} mixing angle by the observation of the muon neutrinos into electron neutrinos oscillations. The experiment started to take data in January 2010 and accumulated 1.43×10^{20} protons on target. Six candidates for the ν_e appearance have been found, with the expected background of 1.5 ± 0.3. The statistical significance of this observation is 2.5σ.

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1. Introduction

The mixing of the neutrino mass eigenstates is described by the Pontecorvo–Maki–Nakagawa–Sakata matrix [1], usually parametrized using three mixing angles θ_{12}, θ_{23}, θ_{13} and one CP-violating phase $\delta_{\rm CP}$. The mixing angle θ_{12} has been determined in the solar [2,3] and reactor experiments [4], and θ_{23} — in atmospheric [5] and accelerator experiments [6,7].

The third mixing angle, θ_{13}, can be measured by the observation of the $\bar{\nu}_e$ disappearance in the short-baseline reactor experiments [8], or by the observation of the $\nu_\mu \rightarrow \nu_e$ oscillation in the long-baseline accelerator experiments [9,10].

In the latter case, the probability of the ν_e appearance can be approximated by the following formula

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

where E_ν is the energy of the neutrino, L — the baseline, and Δm^2_{23} — the squared "atmospheric" mass difference.

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The discovery of the appearance of the electron neutrinos in the muon neutrino beam is the main aim of the T2K experiment. The expected sensitivity is $\sin^2 2\theta_{13} = 0.006$ at 90% C.L. for normal hierarchy of neutrino masses and for the accumulated data corresponding to 8×10^{21} protons on target (POT). The second goal is to provide the precise measurement of the oscillation parameters θ_{23} and Δm^2_{23} by observation of ν_μ disappearance.

The T2K experiment uses the off-axis neutrino beam, which means the angle between the neutrino beam axis and the direction towards the Far Detector is non-zero. The reason for that is related to the pion decay kinematics. When the neutrino is emitted at the non-zero angle, the energy of the neutrino is limited, even for the high-energy pions. The result is more narrow energy spectrum which can be tuned to the maximum oscillation probability by selecting the optimal off-axis angle. The off-axis angle for T2K is 2.5°, and the corresponding peak energy of neutrinos is 600 MeV. The flux at higher energies is reduced, suppressing the background from the production of pions in the neutrino interactions. To keep the peak energy stable, the variation of the neutrino beam center must be precisely controlled.

2. The experiment

The detailed description of the experiment can be found in [11]. In this article, only some basic features are presented.

The neutrino beam is produced in the J-PARC facility in Tokai, Japan. The high-intensity proton beam is accelerated by the accelerator complex up to energy of 30 GeV. Every 3 s the protons are extracted and transported in 8 bunches to the graphite target. The positively charged hadrons produced in the interactions (mostly pions and kaons) are focused by three magnetic horns and directed into 96 m long decay pipe. Here most of the pions and kaons decay, mainly in muons and muon neutrinos. The expected ν_e contamination of the beam is about 1% (0.4% at the oscillation maximum) and comes mostly from the decays of kaons and muons.

All the remaining particles, except for neutrinos and high-energy muons, are stopped in the beam dump, positioned at the end of the decay volume. The escaping muons are measured on the spill-by-spill basis by the Muon Monitor, located downstream the beam dump, and provide an on-line information about the neutrino beam intensity and direction. The beam position resolution is 3 cm, which corresponds to the 0.25 mrad accuracy of the direction.

A schematic view of the neutrino beamline is shown in Fig. 1. The Near Detector complex is placed at the distance 280 m downstream of the target and consists of an on-axis detector (INGRID) and an off-axis detector (ND280), positioned at the same off-axis angle as the Far Detector.

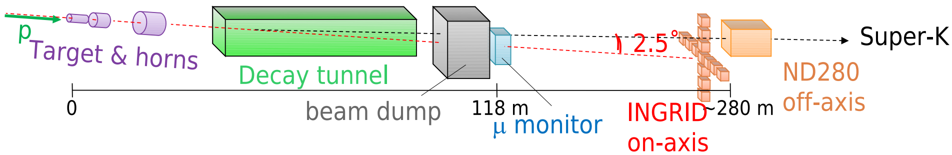

Fig. 1. Schematic view of the T2K neutrino beamline and near detectors.

INGRID is composed of 16 identical modules, 14 arranged in a cross shape, and 2 at diagonal positions (see Fig. 2, left). The center of the cross corresponds to the neutrino beam center. Each module consists of the iron plates and scintillator planes in the sandwich structure. INGRID measures the charged-current neutrino interactions to reconstruct the profile and direction of the neutrino beam.

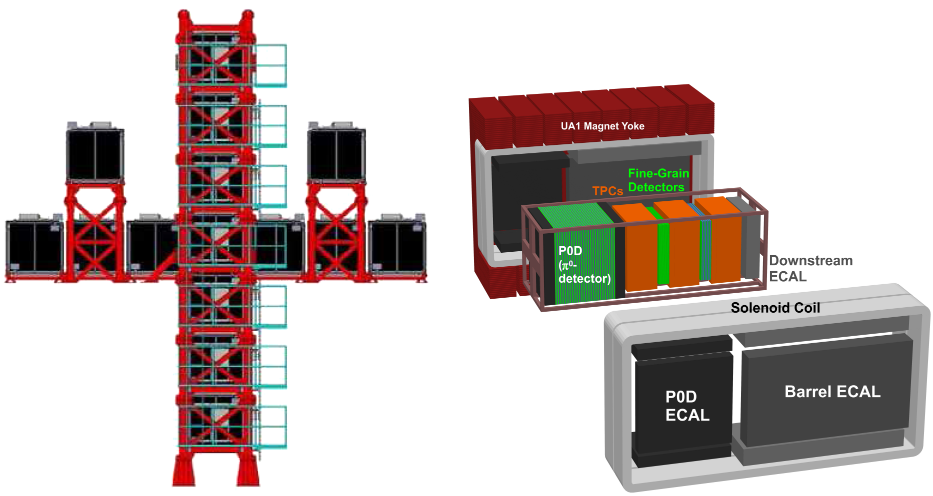

Fig. 2. The set of T2K near detectors: INGRID (left) and ND280 (right).

The ND280 is the multi-purpose set of subdetectors installed inside the magnet (recycled from the UA1 experiment at CERN) and was designed to provide measurements of the un-oscillated neutrino beam spectrum and the dominant background sources, namely the intrinsic ν_e contamination in the beam and the π^0 production in neutral current interactions.

The schematic view of the ND280 subdetectors is shown in Fig. 2, right. The π^0 detector (P0D) is composed by sandwich structure of scintillator planes, lead plates and water target. P0D is designed to study the neutrino interactions with production of π^0.

The tracker, composed by two Fine Grained Detectors (FGD) and three Time Projection Chambers (TPC), is placed downstream the P0D and allows to precisely measure the final states of the neutrino interactions in order to reconstruct the energy spectrum of the neutrino beam. The FGDs consists of the layers of scintillator bars and provides an active target mass and the tracking of the charged particles. The TPCs are able to measure the momentum from the track curvature in the magnetic field with the resolution better than 10% at 1 GeV and provides the particle identification using the energy loss.

The P0D and tracker are surrounded by electromagnetic calorimeter, which detects the escaping electrons and photons, and Side Muon Range Detector, allowing to better measure and identify the muons escaping at high angles.

The Far Detector of the T2K experiment is the large water Cherenkov detector, Super-Kamiokande (SK). The detector has 22.5-kton fiducial mass and consists of two concentric cylindrical regions: the inner detector, equipped with 11129 photomultipliers, and the outer detector, instrumented with 1886 photomultipliers and used to veto events with charged particles entering or exiting the inner detector. The neutrino interactions are identified by the Cherenkov rings produced by relativistic charged products of the interactions, traversing the ultra-pure water in the detector.

SK can identify muons and electrons by analyzing the Cherenkov ring pattern. The electron produces a fuzzy ring, due to the electromagnetic showers and scattering, and the ring produced by a muon has sharp edges. The probability of the misidentification of muons as electrons is about 1%. The details about the SK detector and the reconstruction can be found in [12, 13].

The T2K first physics run took place from January to June 2010. The second run started in November 2010 and was interrupted by the Great East Japan Earthquake on March 11th, 2011. During those two runs, the total number of 1.43×10^{20} POTs was delivered (about 2% of the planned final exposure). The operation of the beamline and the detectors was stable over the whole period of data-taking and the neutrino beam profile and absolute rate was stable and consistent with expectations.

3. The oscillation analyses

The signal of the neutrino oscillations can be observed as an excess (for ν_e appearance) or deficit (for ν_μ disappearance) of single-ring events (electron- or muon-like, respectively) in the sample of charged current quasi-elastic events (CCQE). The CCQE interactions are dominant at T2K energies and allow for the reconstruction of the neutrino energy.

The background for the ν_e appearance comes mostly from the charged current interactions of the intrinsic electron neutrinos and the neutral current interactions of high-energy neutrinos that produce π^0. The π^0 decays can be misidentified as a single electron ring, if the two rings overlap or one of the photons has low energy and missed.

3.1. Prediction of the neutrino flux and interaction rates

The neutrino flux is predicted using the simulation of the protons interactions with the T2K target and the propagation of the secondary particles through the target material, magnetic horns and decay volume. The initial conditions for the protons in the simulation are based on the measurements from the proton beam monitors. The production of the pions is modeled with the data from NA61 experiment [14], and other interactions are simulated with FLUKA [15]. The propagation of the particles outside the target is processed with GEANT 3 [16]. The uncertainty of the flux prediction is dominated by the meson production and cross-sections and can be reduced by the normalization with ND280 data (see the next section).

The interactions of the neutrinos in the detectors are simulated with the NEUT Monte Carlo generator [17]. The uncertainties of the interaction models are determined from the variation of the models parameters and the comparison with the available data. The dominant sources of the uncertainty are the final state interactions of the pions in the nuclei and the cross-sections for neutrino interactions.

The total systematic uncertainty for the ν_e appearance analysis, with the contributions from various sources, is shown in Table I.

TABLE I

The contributions to the total relative uncertainty on the number of electron-like events expected at the Super-Kamiokande.

Source	$\sin^2 2\theta_{13} = 0$	$\sin^2 2\theta_{13} = 0.1$
Neutrino flux	$\pm 8.5\%$	$\pm 8.5\%$
Near detector systematics	$^{+5.6}_{-5.2}\%$	$^{+5.6}_{-5.2}\%$
Near detector statistics	$\pm 2.7\%$	$\pm 2.7\%$
Cross-section	$\pm 14.0\%$	$\pm 10.5\%$
Far detector systematics	$\pm 14.7\%$	$\pm 9.4\%$
Total	$^{+22.8}_{-22.7}\%$	$^{+17.6}_{-17.5}\%$

3.2. The input from ND280 detector

The signal and background predictions for the near detector can be compared to the collected data. The ratio of the POT normalized rates of ν_μ CC interactions in data and Monte Carlo measured at ND280 is then used to renormalize the prediction for SK

$$N_{\mathrm{SK}}^{\mathrm{exp}} = N_{\mathrm{ND280}}^{\mathrm{data}}/N_{\mathrm{ND280}}^{\mathrm{MC}} \times N_{\mathrm{SK}}^{\mathrm{MC}}\,.$$

The prediction is thus constrained by the ND280 data and the absolute event rate uncertainty is significantly reduced. Namely, the uncertainty of the $N_{\mathrm{SK}}^{\mathrm{MC}}$ is 16.1%, while for the $N_{\mathrm{SK}}^{\mathrm{MC}}/N_{\mathrm{ND280}}^{\mathrm{MC}}$ is 8.5%, thanks to the cancellation of common errors.

The ND280 completed the inclusive analysis of the ν_μ CC interactions in the tracker, accumulated with 2.88×10^{19} POT. The comparison with the NEUT based Monte Carlo simulation allowed to produce the data/MC ratio equal to

$$N_{\mathrm{ND280}}^{\mathrm{data}}/N_{\mathrm{ND280}}^{\mathrm{MC}} = 1.036\pm0.028\,(\mathrm{stat.})\,^{+0.044}_{-0.037}\,(\mathrm{det.\,sys.})\pm0.038\,(\mathrm{phys.\,model})\,.$$

The detector systematic uncertainty includes the tracking and particle identification efficiencies. The physics model uncertainty was determined in the studies concerning the cross-sections and final state interactions within NEUT.

3.3. The event selection in Super-Kamiokande

The selection criteria were fixed by the Monte Carlo studies before the data were collected and allow to obtain a CCQE enhanced sample of interactions of oscillated electron neutrinos by choosing the single-ring electron-like events. The selection efficiency was estimated to be 66% and the background reduction is 99% for NC events with misidentified π^0 and 77% for intrinsic ν_e CC interactions.

The fully-contained fiducial volume (FCFV) sample consists of 88 events, which passed the following criteria:

1. no activity in the Outer Detector or 100 μs before the beam trigger time,
2. $>$ 30 MeV energy deposited in the Inner Detector,
3. reconstructed vertex in the fiducial region.

The requirement of a single ring was fulfilled by 41 events, 8 of those were electron-like and 33 were muon-like.

3.4. The results of ν_e appearance analysis

Additional cuts were imposed to enhance the purity of the sample, *i.e.*:

1. visible energy $>$ 100 MeV, to reduce the background from neutral current interaction,
2. no delayed activity, to reject the electrons from muon decays,
3. after the forced reconstruction of 2 rings, the invariant mass must be $<$ 105 MeV, to remove NC events with misidentified π^0,
4. reconstructed neutrino energy (with the assumption of quasi-elastic kinematics) must be $<$ 1250 MeV, to suppress the interactions of the intrinsic ν_e component.

The number of events passing the criteria is shown in Table II. After all cuts were applied, 6 candidate events remain. The further examination showed their properties to be consistent with ν_e CC interactions.

TABLE II

Summary of the events passing the cuts.

Cut	Data	Expectation for $\theta_{13} = 0$
FCFV	88	73.9
Single ring	41	38.5
Electron-like	8	6.8
$E_{\rm vis} > 100$ MeV	7	5.9
No delayed activity	6	4.6
π^0 cut	6	2.0
$E_\nu < 1250$ MeV	6	1.5

The events vertices were found to be clustered near the edge of the fiducial volume in the upstream direction. The Kolmogorov–Smirnov test was performed on the squared radius distribution and yielded 3% probability of such configuration. The additional tests of the possible beam-related background, the efficiency of the reconstruction algorithm and the activity in the Outer Detector showed no reason to reject those events as background.

If θ_{13} is zero, the expected number of events passing all the SK cuts is 1.5 ± 0.3 and the contributions to this number are shown in Table III. The probability of observing 6 events for the expectation of 1.5 is 0.7%, which is equivalent to 2.5σ statistical significance.

The best fit to the data indicates the $\sin^2 2\theta_{13}$ to be 0.11 (0.14) for normal (inverted) hierarchy of neutrino masses and $\delta_{\rm CP} = 0$. The 90% confidence intervals, produced with the unified Feldman–Cousins method, are $0.03\,(0.04) < \sin^2 2\theta_{13} < 0.28\,(0.34)$. The confidence intervals are shown in Fig. 3, together with the best fit values for different values of $\delta_{\rm CP}$.

TABLE III

The contributions to the expected number of events after all cuts for $\theta_{13} = 0$.

Intrinsic ν_e CC	0.8
All NC	0.6
$\nu_\mu \to \nu_e$ via subleading solar term	0.1
Total	1.5

The T2K results was further constrained by the new MINOS measurement, published few days later [18]. The MINOS 90% allowed regions are also shown in Fig. 3.

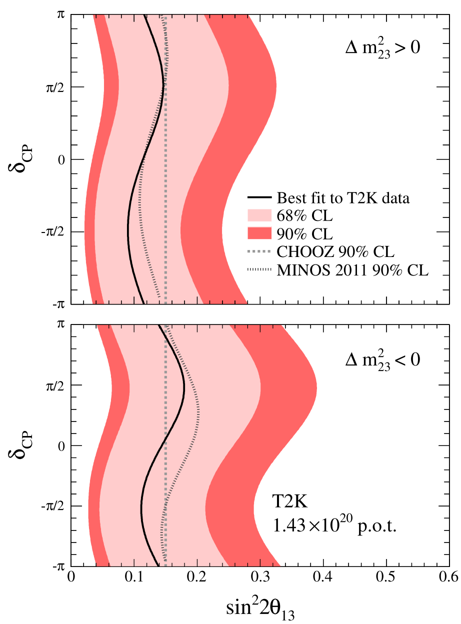

Fig. 3. The confidence intervals for $\sin^2 2\theta_{13}$ for normal (top) and inverted (down) mass hierarchy. The MINOS allowed region is marked by dotted line.

3.5. The results of ν_μ disappearance analysis

To improve the sample of muon-like single-ring the events were demanded to have less than 2 decay electrons and the track momentum higher than 200 MeV/c. There were 31 events passing the criteria. The events vertices were distributed uniformly in the fiducial volume.

The expected number of events without oscillations is 103.59 ± 10.18 (stat.) ${}^{+13.77}_{-12.43}$ (syst.). The observation of 31 candidates allows to exclude the null oscillation hypothesis at 4.4σ level.

The data were analyzed with two independent methods in order to extract the oscillation parameters. One method was based on the maximum likelihood, with fitting of the systematics parameters, and the other one compared the observed and expected spectrum, varying the oscillation parameters to minimize the χ^2 function. The obtained best fit values were $|\Delta m^2_{23}| = 2.6 \times 10^{-3}$ eV, $\sin^2 2\theta_{23} = 0.99\,(0.98)$, for the first and second method, respectively.

The 90% confidence intervals are shown in Fig. 4, together with the results of Super-Kamiokande and MINOS.

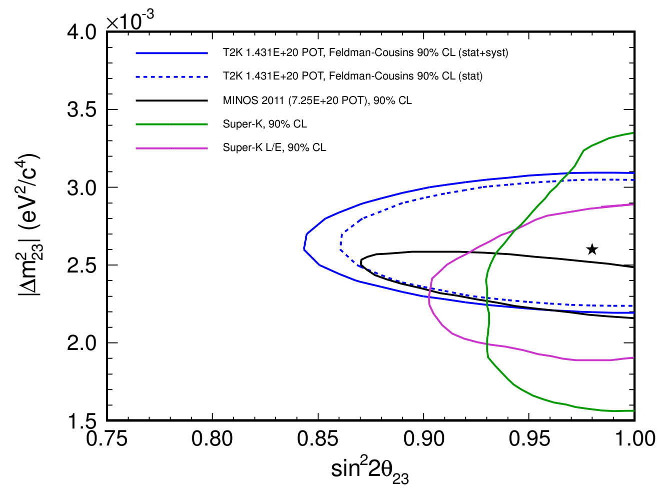

Fig. 4. The 90% confidence intervals for the ν_μ oscillation analysis, compared to the Super-Kamiokande and MINOS results.

4. Future plans

The T2K experiment is recovering after the Great East Japan Earthquake. No serious damages were found in the accelerator complex, the neutrino beamline or the near detectors. The Super-Kamiokande detector was not affected by the earthquake. The J-PARC facility is expected to resume operations in December 2011 and T2K experiment will restart the data-taking as soon as possible.

The aim of the experiment is to accumulate 10^{21} POT in summer 2013. Such data sample will allow to confirm the non-zero value of θ_{13} with 5σ statistical significance (at the present best fit value).

REFERENCES

[1] Z. Maki, M. Nagakawa, S. Sakata, *Prog. Theor. Phys.* **28**, 870 (1962).

[2] J. Hosaka *et al.*, *Phys. Rev.* **D73**, 112001 (2006).

[3] B. Aharmim *et al.*, *Phys. Rev.* **C72**, 055502 (2005).

[4] S. Abe *et al.*, *Phys. Rev. Lett.* **100**, 221803 (2008).

[5] Y. Ashie *et al.*, *Phys. Rev.* **D71**, 112005 (2005).

[6] M.H. Ahn *et al.*, *Phys. Rev.* **D74**, 072003 (2006).

[7] P. Adamson *et al.*, *Phys. Rev. Lett.* **106**, 181801 (2011).

[8] M. Apollonio *et al.*, *Eur. Phys. J.* **C27**, 331 (2003).

[9] P. Adamson *et al.*, *Phys. Rev.* **D82**, 051102 (2010).

[10] K. Abe *et al.*, *Phys. Rev. Lett.* **107**, 041801 (2011).

[11] K. Abe *et al.*, *Nucl. Inst. Meth.* **A**, in press, doi:10.1016/j.nima.2011.06.067.

[12] S. Fukuda *et al.*, *Nucl. Instr. Meth.* **A501**, 418 (2003).

[13] S. Kasuga *et al.*, *Phys. Lett.* **B374**, 238 (1996).

[14] N. Abgrall *et al.*, *Phys. Rev.* **C84**, 034604 (2011).

[15] G. Battistoni *et al.*, *AIP Conf. Proc.* **896**, 31 (2007); A. Fasso, A. Ferrari, J. Ranft, P.R. Sala, CERN-2005-10, INFN/TC-05/11, SLAC-R-773.

[16] GEANT — Detector Description and Simulation Tool, Application Software Group, Computing and Networks Division, CERN, Geneva 1993.

[17] Y. Hayato, *Nucl. Phys. Proc. Suppl.* **B112**, 171 (2002).

[18] P. Adamson *et al.*, `arXiv:1108.0015v1 [hep-ex]`, accepted by *Phys. Rev. Lett.*