

T2K EXPERIMENT NEUTRINO OSCILLATION RESULTS*

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(Received October 30, 2019)

T2K is a long-baseline experiment built to measure neutrino oscillations. A muon neutrino (anti-neutrino) beam is produced at the J-PARC accelerator complex and sent towards the near detector located 280 meters away from the neutrino source and the far detector at 295 kilometers. The change in the measured intensity and composition of the beam is used to extract the oscillation parameters. The T2K experiment has provided 2σ confidence intervals for δ_{CP} phase and improved the precision of the θ_{23} and Δm_{32}^2 measurement. A summary of the neutrino oscillation results for 1.49×10^{21} POT in neutrino-mode and 1.63×10^{21} POT in anti-neutrino-mode (January 2010–May 2018) is presented.

DOI:10.5506/APhysPolB.50.1757

1. Neutrino oscillations

Neutrinos are very important in the Standard Model of particle physics and cosmology. Their interactions are carried out both via charged current (CC) and neutral current (NC) exchange. The flavor of the neutrino can be determined by the charged lepton that is produced in CC reaction: electron for ν_e , muon for ν_μ and tau for ν_τ interactions. Neutrinos also oscillate which means that they change their flavor from one to another as they travel. This fact was revealed by several experiments including Super-Kamiokande (Super-K) [1].

From the theoretical point of view, neutrino oscillations are a quantum-mechanical effect where the observed neutrino flavor states from the Standard Model ν_e , ν_μ and ν_τ propagate in space as linear combinations of the mass eigenstates ν_1 , ν_2 and ν_3 . The relation between neutrino flavor states

* Presented at the XLIII International Conference of Theoretical Physics “Matter to the Deepest”, Chorzów, Poland, September 1–6, 2019.

and the mass eigenstates is described by the Pontecorvo–Maki–Nakagawa–Sakata (PMNS) matrix, which can be parametrized using three mixing angles θ_{13} , θ_{23} , θ_{12} and one complex phase δ_{CP} . The description of the oscillation probabilities requires two more parameters which are two independent differences of mass squared of the neutrinos: Δm_{21}^2 , $\Delta m_{32(13)}^2$.

Thanks to the discovery of Super-K and other experiments, neutrino oscillation physics became one of the most dynamically developing areas of research in particle physics. Results from Super-K have been confirmed and supplemented later by many experiments. They provided information about all mixing angles and mass splittings with a good precision [2].

Although most of the mixing parameters have been measured, there are still open questions in neutrino oscillation physics. Two of the most important questions are: is there a CP violation in the neutrino sector (is δ_{CP} phase different from 0 or π ?) and what is the neutrino mass ordering related to the sign of $\Delta m_{32(13)}^2$: normal ordering (NO), where $m_3 > m_2 > m_1$ or inverted ordering (IO), where $m_2 > m_1 > m_3$?

2. The T2K experiment

The T2K Collaboration consists of approximately 500 people from 59 institutions in 11 countries. The experiment aims at looking for neutrino oscillations in two channels: $\nu_e(\bar{\nu}_e)$ appearance in the $\nu_\mu(\bar{\nu}_\mu)$ beam and the disappearance of $\nu_\mu(\bar{\nu}_\mu)$ from the beam. The oscillation probabilities for neutrino-mode can be written as follows:

$$P(\nu_\mu \rightarrow \nu_e) \simeq \sin^2 \theta_{23} \sin^2 2\theta_{13} \sin^2 \frac{\Delta m_{31}^2 L}{4E} - \frac{\sin 2\theta_{12} \sin 2\theta_{23}}{2 \sin \theta_{13}} \sin \frac{\Delta m_{21}^2}{4E} \sin^2 2\theta_{13} \sin^2 \frac{\Delta m_{31}^2 L}{4E} \sin \delta_{\text{CP}} + (\text{CP term, solar term, matter term}), \quad (1)$$

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - (\cos^4 \theta_{13} \sin^2 2\theta_{23} + \sin^2 \theta_{23} \sin^2 2\theta_{13}) \sin^2 \frac{\Delta m_L^2}{4E}, \quad (2)$$

where Δm^2 is either Δm_{32}^2 for normal mass ordering or Δm_{13}^2 for inverted mass ordering. One can observe that the probability of ν_e appearance depends on θ_{13} and δ_{CP} , while ν_μ disappearance formula is sensitive to θ_{23} and $\Delta m_{32(13)}^2$. The parameters mentioned above are measured in the T2K experiment.

T2K is a long-baseline neutrino experiment with $\nu_\mu(\bar{\nu}_\mu)$ beam produced by the J-PARC proton accelerator complex. Neutrinos (anti-neutrinos) are sent towards the near detector station at 280 m and the far detector, located 295 km away from J-PARC. A schematic picture of the T2K setup is shown in Fig. 1.

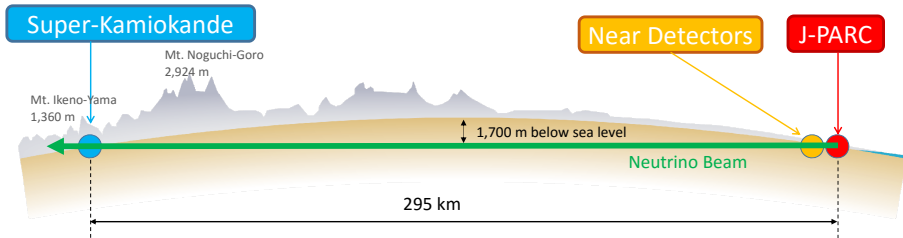


Fig. 1. The setup of the T2K experiment.

The off-axis beam concept is used in T2K to produce a narrow-band neutrino beam with one of the near detectors (ND280) and the far detector located 2.5° away from the main axis. This setup allows T2K to produce a beam with a narrow energy spectrum with a peak at 0.6 GeV which is tuned to the maximum neutrino oscillation probability at 295 km. This configuration also minimizes the background to the ν_e ($\bar{\nu}_e$) appearance measurement.

2.1. Neutrino beam

The T2K neutrino beamline contains two consecutive parts: a primary and secondary beamline. The primary beamline extends from the 30 GeV proton beam from the J-PARC's 'Main Ring' (MR) accelerator up to the target station. In the secondary beamline, the protons extracted from MR interact with the graphite target and produce secondary pions which are focused by a set of magnetic horns. The polarity of the horns can be changed to focus either positively or negatively charged pions and produce either neutrinos or anti-neutrinos. The pions enter a 96 m-long decay volume where they decay and produce muons which are stopped on the beam dump and neutrinos which travel further away to the near and far detectors.

2.2. Near detectors

The near detectors station is located 280 m away from the neutrino target and consists of two main parts: off-axis and on-axis detectors.

The ND280 off-axis detector is built of several sub-detectors encapsulated in the UA1/NOMAD magnet which is the source of a 0.2 T magnetic field. It consists of Pizero detector (P0D), Tracker — containing two Fine-Grained Detectors (FGDs) and three Time Projection Chambers (TPCs) filled with an argon-based gas mixture, Electromagnetic Calorimeter (ECAL) and Side Muon Range Detector (SMRD). The ND280 detector measures the neutrino flux before the oscillation occurs and provides information about the intrinsic ν_e contamination in the beam. It also measures various neutrino cross sections.

The on-axis detector, called INGRID, is composed of 16 iron/scintillator modules and an additional scintillator-only module (proton module). The goal of the INGRID detector is to monitor the beam rate, direction and stability by counting muons from ν_μ charged current interactions. INGRID is also capable of measuring various neutrino cross sections.

2.3. Far detector

The Super-Kamiokande detector is the far detector for the T2K experiment. This is the world's largest 'land-based' water Cherenkov detector, which has been operating since 1996 and its technology and operations are well-understood [3]. The detector is located 1 km underground in the Mozumi mine and is a cylindrical tank filled with 50 kton of pure water. 13 000 photomultipliers on the walls of the tank detect the Cherenkov light (rings) emitted by the charged particles produced in neutrino interactions. A schematic view of the Super-K detector is shown in Fig. 2. The Super-Kamiokande detector has a well-established electron-muon discrimination technique which is very important for distinguishing between ν_e and ν_μ interactions. The Cherenkov rings in the detector can be classified as electron-like or muon-like, depending on their appearance. The muon ring has sharp edges while the electron ring is more fuzzy because of the showering. The mis-identification for a muon as an electron and *vice versa* is less than 1%.

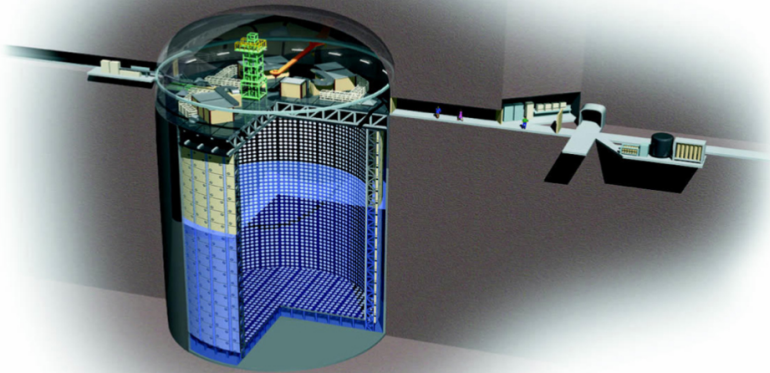


Fig. 2. Schematic view of Super-Kamiokande detector.

3. Neutrino oscillation measurements at T2K

The T2K experiment has been collecting physics data since the beginning of 2010 and exceeded 3.16×10^{21} protons on target (POT) as on May 31, 2018. In the analyses presented in this paper, 1.49×10^{21} POT for neutrino-mode and 1.63×10^{21} POT for anti-neutrino-mode has been used. In the strategy for the neutrino oscillation measurements in T2K, the data collected by both the near and far detector are crucial. The data from the near detector (ND280) is fitted using several inputs: neutrino flux prediction, neutrino cross section models and their uncertainties and uncertainties for the event selection in the near detector. The output of the ND280 fit along with the far detector systematic uncertainties are used as inputs for the far detector fit. A fit to the Super-K data is performed using the PMNS neutrino oscillation model and provides the estimates for the oscillation parameters. An alternative approach, where both far and near detector data are fitted simultaneously, has also been developed.

The analysis of the near detector data allows one to reduce the uncertainties in the far detector. Multiple data samples in ND280 are fitted to constrain the combination of the flux and neutrino interaction systematic errors at Super-K. There are six samples (carbon and water targets) for neutrino-mode: ν_μ CC0 π , ν_μ CC1 π , ν_μ CCOther and eight samples for anti-neutrino-mode: $\bar{\nu}_\mu$ CC1Track, $\bar{\nu}_\mu$ CCNTrack, ν_μ CC1Track, ν_μ CCNTrack. Data on carbon and water targets are binned in outgoing muon momentum and angle. Fitting the near detector data allows the flux and cross section uncertainties to be reduced from 15% to 5%. Many improvements have also been made to the Super-K data analysis. Apart from the well-established ν_e and ν_μ CCQE samples (only electron/muon in the final state), the new ν_e CC1 π sample (additional Michel electron from pion decay) has been introduced into the analysis. Improvements also include: an optimized fiducial volume cut and a new reconstruction algorithm (fitQun). There are 75 ν_e CCQE, 15 ν_e CC1 π and 243 ν_μ candidates selected in the Super-K detector after all analysis cuts. The number of ν_e and ν_μ anti-neutrino candidates is 9 and 102, respectively. A binned maximum-likelihood fit to all far detector samples is done simultaneously.

Observed event rates prefer $\delta_{\text{CP}} = -\pi/2$. The marginalization procedure is performed over all nuisance parameters to get the oscillation probabilities as a function of parameters of interest. A detailed procedure of the validation of results is performed including: comparisons across independent fitting approaches (frequentist *vs.* Bayesian statistics), comparisons between different far-detector data binning approaches (one-dimensional with neutrino energy *vs.* two-dimensional with outgoing lepton momentum and angle) and

pseudo-data fits. The result of the study of atmospheric neutrino oscillation parameters in T2K with additional constraint on θ_{13} angle from reactor experiments is shown in Fig. 3.

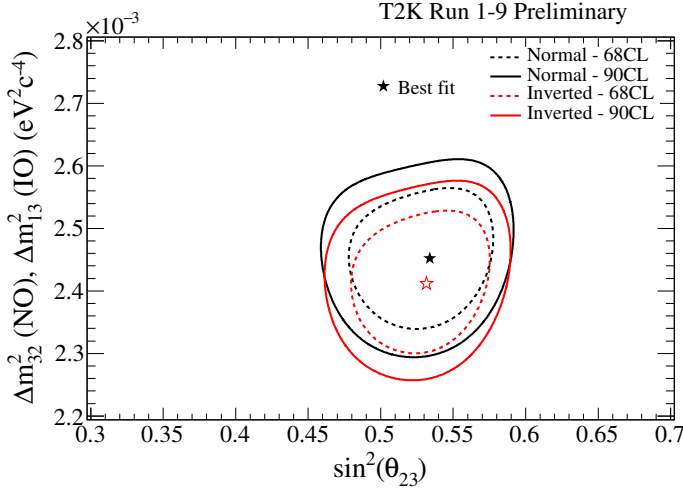


Fig. 3. The 68% and 90% C.L. allowed regions for $\sin^2 \theta_{23}$ and $\Delta m^2_{32(13)}$ provided by the T2K experiment with additional constraint from the reactor experiments.

One can observe that T2K results are consistent with $\theta_{23} = 45^\circ$. The preferred value of θ_{13} from the T2K experiment alone also agrees with the results from reactor-neutrino experiments within the uncertainties as seen in Fig. 4.

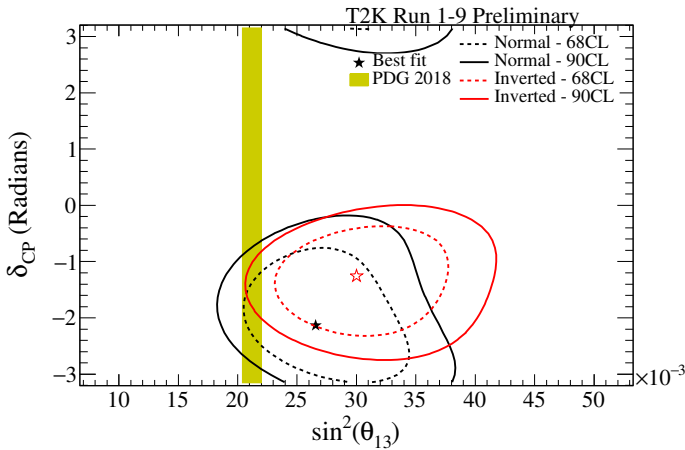


Fig. 4. Allowed regions for $\sin^2 \theta_{13}$ and δ_{CP} from T2K and the result from reactor experiments (gray/yellow band).

The analysis of the T2K data with the reactor constraint excludes regions of δ_{CP} at 2σ (Fig. 5).

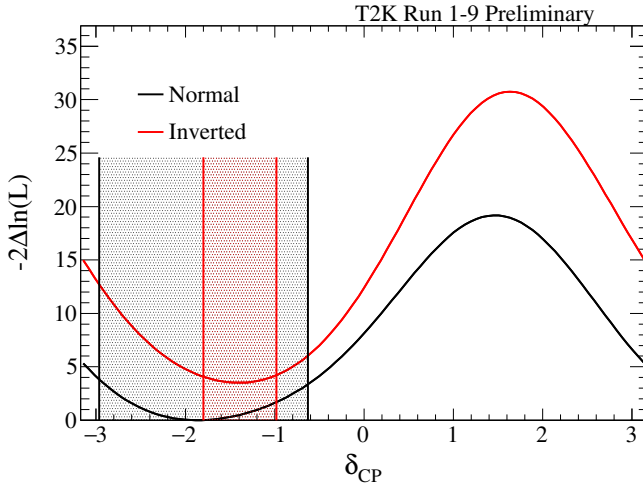


Fig. 5. 2σ confidence regions for δ_{CP} phase provided by the T2K experiment.

Values of δ_{CP} which conserve CP symmetry ($0, \pm\pi$) fall outside of 2σ region for both normal and inverted mass ordering, and 2σ intervals are as follows: $[-2.966, -0.628]$ — for normal ordering and $[-1.799, -0.979]$ — for inverted. The best fit value of δ_{CP} for normal ordering is -1.885 rad.

4. The future of T2K

An extension of the running period of the T2K experiment has been proposed with increased beam power and upgraded near detector. The Main Ring accelerator will be upgraded to reach the beam intensity of 1.2 MW and the upgrade of ND280 [4] will be installed by 2021 allowing to increase the angular acceptance and to lower the threshold for reconstructing particles, notably for protons. The plan is to reduce the systematic errors down to 4% with the upgraded beam and near detector. The second stage of T2K is expected to reach 3σ CP-violation sensitivity.

5. Summary

The neutrino oscillation analysis in the T2K experiment presented in this paper uses 1.49×10^{21} and 1.63×10^{21} POT for neutrino-mode and anti-neutrino-mode, respectively. T2K is working with high intensity and stable neutrino (anti-neutrino) beam with 470 kW of power. With this amount of data, the experiment has provided the world's best measurement of the θ_{23}

mixing angle (consistent with $\theta_{23} = 45^\circ$) and delivered 2σ confidence intervals for δ_{CP} : $[-2.966, -0.628]$ for normal mass ordering and $[-1.799, -0.979]$ for inverted ordering. Many improvements in the analyses have lead to a 20% increase of number of selected events in the far detector. The T2K experiment has also a broad neutrino cross section program and is producing a lot of important cross-section results. Extensive work is being performed in T2K to search for the best methodology for neutrino–nucleus cross-section measurements with minimal model dependence. The first stage of the proposal to extend the running of the T2K experiment to 2026 to achieve 3σ CP-violation sensitivity has been approved.

This work was supported by the Polish Ministry of Science and Higher Education, project number: DIR/WK/2017/05.

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