Latest (Anti) Neutrino Oscillation Results from T2K

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Abstract. The T2K long-baseline neutrino oscillation experiment has been running since 2010; it collects data in both neutrino and anti-neutrino modes. The results presented here refer to a joint analysis of νμ disappearance and νe appearance for neutrino data giving the world-leading measurements of δCP, θ23 and Δm23. The first anti-neutrino beam results are also discussed here which allows for testing of CPT symmetry and an electron anti-neutrino appearance search.

1. Introduction

Neutrinos are the only elementary particles which can spontaneously change flavour. This phenomenon is called “neutrino oscillation”. Since we have three neutrino types of different flavour (νe, νμ, and ντ), we can observe mixing of all three types of neutrinos. Neutrino oscillations were proven to exist by two experiments. The Super-Kamiokande experiment first announced discovery of neutrino oscillations in 1998, using measurements of atmospheric neutrinos [1]. A few years later their results were followed by proof of neutrino oscillations in the solar neutrino sector by the SNO experiment [2]. Both of those discoveries were awarded the Nobel Prize in Physics in 2015. Those studies have been followed by measurements of neutrino oscillations under controlled conditions using artificially produced neutrino beams. The first experiment of that type was K2K [3], later followed by the MINOS [4] and OPERA [5] experiments. The T2K experiment (which results are discussed here) [6] and NOvA are the currently running long-baseline neutrino oscillation experiments. They are dedicated to answer still unknown questions in neutrino physics. On the one side they provide precise measurement of oscillation parameters such as θ12, θ13 and Δm23 [7,8]. They also try to answer the questions of wether CP symmetry is violated or conserved in neutrino sector, and what is the neutrino mass hierarchy.

Neutrino oscillations are possible because neutrino flavour states are not identical to neutrino mass eigenstates. They are mixed as described by the Pontecorvo-Maki-Nakagawa-Sakata mixing matrix:

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix} =
\begin{pmatrix}
U_{e1} & U_{e2} & U_{e3} \\
U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\
U_{\tau 1} & U_{\tau 2} & U_{\tau 3}
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
\]

That matrix can be parameterized by the three mixing angles θ12, θ13, and θ23 and one CP violating phase δCP as shown here:
The probability for neutrinos to change flavour can be expressed as:

\[
U = \begin{pmatrix}
1 & 0 & 0 \\
0 & \cos\theta_{23} & \sin\theta_{23} \\
0 & -\sin\theta_{23} & \cos\theta_{23}
\end{pmatrix} \begin{pmatrix}
\cos\theta_{13} & 0 & \sin\theta_{13} e^{-i\Delta m^2_{12}} \\
0 & 1 & 0 \\
-\sin\theta_{13} e^{i\Delta m^2_{12}} & 0 & \cos\theta_{13}
\end{pmatrix} \begin{pmatrix}
\cos\theta_{12} & \sin\theta_{12} & 0 \\
-\sin\theta_{12} & \cos\theta_{12} & 0 \\
0 & 0 & 1
\end{pmatrix}
\]

The probability for neutrinos to change flavour can be expressed as:

\[
P(\alpha \rightarrow \beta) = \left| \sum_{i,j} U^*_{\alpha i} U_{\beta j} U^*_{\alpha j} U_{\beta i} e^{i \frac{L \Delta m^2_{ij}}{2E}} \right|
\]

In general, neutrino oscillations can occur only when two conditions are fulfilled: the mixing angle is not equal to zero, and \(\Delta m^2=\text{m}^2_{i}-\text{m}^2_{j}\) is not zero. Therefore, observation of neutrino oscillations proves that neutrinos are not massless. Measurements of neutrino mixing parameters allow us to experimentally probe neutrino masses by measuring the mass squared differences (\(\Delta m^2\)). The T2K experiment studies neutrino oscillations using an accelerator-produced neutrino beam by measuring probability of \(\nu_\mu\) to disappear, so called \(\nu_\mu \rightarrow \nu_\mu\) oscillations. It was also the first experiment in the world to measure the appearance of \(\nu_e\) from the \(\nu_\mu\) beam (\(\nu_\mu \rightarrow \nu_e\) oscillation). T2K is currently measuring neutrino oscillations in an anti-neutrino beam, which could lead to discovery of CP violation in the neutrino sector. Consequently it is able to study the disappearance on anti-neutrinos via anti-\(\nu_\mu\) oscillation and tries to measure the appearance of anti-\(\nu_e\) in anti-\(\nu_\mu\) beam (anti-\(\nu_\mu \rightarrow \nu_e\) oscillations). The first of these transformations can provide a test of the CPT symmetry. This is due to the fact that the probability of muon neutrinos to survive, \(P(\nu_\mu \rightarrow \nu_\mu)\), depends on \(\cos\delta_{CP}\) only; therefore all terms are CP conserving. The situation is different when we try to probe the appearance of electron neutrinos, \(\nu_\mu \rightarrow \nu_e\). The probability which describes that transformation has CP violating terms which depend on \(\sin\delta_{CP}\). If CP is violated, we expect a different probability for neutrinos to oscillate than for the situation when \(\delta_{CP}\) equals 0 or \(\pi\). On the other hand, the probability of anti-neutrinos to oscillate as anti-\(\nu_\mu \rightarrow \nu_e\) will be different that for neutrino oscillations of \(\nu_\mu \rightarrow \nu_e\) if \(\delta_{CP}\) is not zero or \(\pi\). The maximum effect of the CP violation corresponds to the value of \(\delta_{CP}\) equals +/-\(\pi/2\).

That paper will summarize results of neutrino and anti-neutrino oscillations measurements performed by the T2K experiment.

2. Overview of the T2K experiment

The T2K experiment is an accelerator neutrino experiment located in Tokai, Japan which uses a 30 GeV proton beam produced by the JPARC accelerator to create an almost pure \(\nu_\mu\) beam. Protons are collided with a graphite target where they produce positive and negative pions and kaons as a result of the interaction. Those charged particles are focused by three horn magnets which select either positive or negative pions. When \(\pi^+\) are selected then they produce a \(\nu_\mu\) beam. Alternatively, when the horns are operated in the so-called “reverse horn current mode” the \(\pi^-\) are focused and sent to the decay pipe, where they decay to produce the anti-\(\nu_\mu\) beam. The T2K experiment started operation in 2010 and was analyzed 6.2x10^20 POT (protons on target) of neutrino beam data. Since 2014, we have been collecting data for the anti-neutrino mode. The results presented here are based on the analysis of the 4.0x10^20 POT collected statistics from the anti-neutrino run.

The experiment is composed of near and far detector stations. One of the near detectors, INGRID, is placed on the beam axis and used to monitor the beam intensity and stability during operation. The other near detector station, called ND280, is placed 280m from the neutrino production point to study the unoscillated neutrino beam. The phenomena of oscillations are measured by the Super-Kamiokande (SK) far detector which is located 295km from the beginning of the neutrino beam. SK is a water Cherenkov detector which records muons and electrons coming out of charged current interactions of (anti-)\(\nu_\mu\) and (anti-)\(\nu_e\) [9]. It is a cylindrical water tank 41m high and 39m diameter placed 1km underground. SK has the ability to distinguish between \(\nu_\mu\) and \(\nu_e\) events by studying the
pattern of the Cherenkov ring seen by the photosensors. The misidentification probability is less than 1%. Consequently we can study $\nu_\mu \rightarrow \nu_\mu$ and $\nu_\mu \rightarrow \nu_e$ oscillations separately.

3. Overview of oscillation analysis
In order to perform oscillation analysis, the initial inputs of neutrino flux prediction and cross-sections of $\nu$ interactions are necessary. The NA61/SHINE experiment at CERN delivers spectra of neutrino parents, mostly $\pi$ and $K$, coming from interactions of a proton beam on a carbon target. Such measurements are used to tune the multiplicity of corresponding particles in the T2K beam simulation. This allows prediction of neutrino flux with precision as good as 10% [10]. External data from MiniBooNE and Minerva are used to model neutrino interaction cross-sections. As a next step, the near detector data of the T2K experiment are used to perform a fit which allows us to constrain flux and cross-section parameters (as described in Section 4). Using that information, predictions of event rates in the far detector Super-Kamiokande, are made. Selection of neutrino data in SK is described in Ref.[11]. The predicted number of events and their spectra are compared with the detected $\nu_\mu$ and $\nu_e$ induced events in the far detector to derive the oscillation parameters.

4. Near Detector measurement
The near detector, ND280, has an important role to provide the reference measurement of unoscillated neutrino flux and measure cross-sections of neutrino interactions. The ND280 is a tracker detector which is placed inside the former UA1/NOMAD magnet creating a 0.2T magnetic field. For the analysis presented in this paper, neutrino interactions in the Fine-Grained Detector (FGD) – a scintillator detector, were analyzed. The FGD is interlayed with Time Projection Chamber detectors (TPC). These ensure tracking of the particles coming out of $\nu$ interactions, their identification and momentum reconstruction. The Electromagnetic Calorimeter and Side Muon Range Detector are used to measure particles escaping the tracker volume.

Thanks to the fact that detector is placed in a magnetic field, we are able to distinguish interactions of $\nu$ from anti-$\nu$ by identifying the sign of the outgoing lepton. The analysis of near detector data relies on information about the presence of the $\pi^-$ in the interaction. The selected sample of $\nu_\mu$ charged current events are split into sub-categories based on whether $\pi^-$ were present in the interaction, or whether there were more charged or neutral pions present. It allows us to be sensitive to various types of neutrino interaction processes such as charged current quasi elastic interactions (with no pions coming out of the interaction), processes where pions are produced through the resonances, and deep inelastic interactions. Consequently, the near detector data measurement provides a detailed $\nu_\mu$ and $\nu_e$ flux measurement and allows us to reduce the predicted flux uncertainty in the far detector [11]. It also allows us to constrain parameters describing different models of neutrino interaction cross-sections. To summarize: the flux and cross-section related systematic uncertainty on predicted number of $\nu_\mu$ events in SK is reduced from 9.2% to 3.4% when the near detector measurement is taken into account.

5. Oscillation analysis results

5.1 Neutrino data results
The neutrino data were collected from 2010 until 2013 and correspond to $6.2\times10^{20}$POT of analyzed statistics [11]. For that period, 120 $\nu_\mu$-induced events were observed in the Super-Kamiokande far detector when $446.0\pm22.5$ are expected in case of no oscillation (for $\sin^22\theta_{23}=0.0$). Therefore, a clear disappearance signal for $\nu_\mu$ is observed. In case of the maximal mixing ($\sin^22\theta_{23}=1.0$) the expected number of $\nu_\mu$ events is $125.85$ ($\Delta m^2_{3\alpha}=2.4\times10^{-3} eV^2/c^4$ is assumed).

When the $\nu_e$ selection is applied in the Super-Kamiokande data, then 28 data events are found. In the case of no $\nu_\mu \rightarrow \nu_e$ oscillation ($\sin^22\theta_{13}=0.0$), the predicted background is $4.92\pm0.55$ which is estimated based on assumption of other oscillation parameters ($\sin^22\theta_{23}=1.0$, $\Delta m^2_{3\alpha}=2.4\times10^{-3} eV^2/c^4$ and
For $\sin^2 \theta_{13} = 0.1$ we expect to find 21.59 $\nu_e$ events. Consequently the evidence of the $\nu_\mu \rightarrow \nu_e$ transition is observed.

We perform a combined 3-flavour simultaneous fit to the energy spectra of $\nu_\mu$-induced and $\nu_e$-induced events. It allows us to be sensitive to correlations between oscillation parameters. During the fit, the four parameters $\Delta m^2_{23}$, $\sin^2 \theta_{23}$, $\sin^2 \theta_{13}$ and $\delta_{CP}$ are simultaneously determined. As a result, we obtain the world best and most precise measurement of $\sin^2 \theta_{23}=0.524\pm0.057-0.059$ (normal hierarchy) and $0.523\pm0.055-0.065$ (inverted hierarchy). The allowed region of mixing parameters are shown on the left plot in Fig.1 alongside the MINOS and Super-Kamiokande atmospheric neutrino results. The results for the other mixing angle gives $\sin^2 \theta_{13}=0.042\pm0.013-0.021$ (normal hierarchy) and $0.049\pm0.015-0.021$ (inverted hierarchy). The allowed region of parameters in $\delta_{CP}$ and $\sin^2 \theta_{13}$ phase space is shown in the right plot of Fig.1. When we combine the T2K results with the most precise measurement of the $\theta_{13}$ mixing parameter (obtained by reactor experiment [12]), then the allowed region of these parameters shrinks. Based on analyzed statistics of data reported here T2K-only could not claim sensitivity to $\delta_{CP}$. However, when the reactor results are used, then both experiments together start to be sensitive to $\delta_{CP}$. As a result we can exclude $\delta_{CP}=[0.15,0.83]\pi$ for the normal hierarchy and $\delta_{CP}=[-0.08,1.09]\pi$ for the inverted hierarchy at 90% confidence level. We can also conclude that the favored value of $\delta_{CP}$ is $-\pi/2$.

### 5.2 Anti-neutrino data results

The anti-neutrino data were collected from 2014 and the results presented in this paper correspond to $4.0\times10^{20}$POT. For the anti-neutrino run, the anti-$\nu_e$ disappearance and anti-$\nu_\mu$ appearance analyses were performed separately [13, 14].
There are 34 muon-like events found in the anti-neutrino run at the far detector. Super-Kamiokande detector cannot distinguish $\nu^-$ from $\mu^-$ and, therefore, can not specify if it was $\nu_\mu$ or anti-$\nu_\mu$ interacting. Here we refer to the accelerator produced neutrino or anti-neutrino beam for the specific run which was analyzed. In case of no oscillation, the expected number of events is 103.6 (for $\sin^2 2\theta_{23}=0.0$). The clear signature of observed anti-$\nu_\mu$ disappearance is shown on the energy spectrum distribution of muon events in the left plot of Fig.2. During the fitting of anti-$\nu_\mu$ data, all oscillation parameters were fixed except $\sin^2 \theta_{23}$ and $\Delta m^2_{32}$. The results, presented on the right plot of Fig.2 shows that the obtained mixing parameters for anti-neutrinos are consistent with those measured by T2K for the neutrino beam (indicating that CPT is conserved). The results are also consistent with other measurements of anti-neutrinos performed by MINOS and Super-Kamiokande. The measured values for the oscillation parameters were found to be $\sin^2 \theta_{23}=0.45\pm0.38-0.64$ and $|\Delta m^2_{32}|=2.51\pm0.29-0.26 \times 10^{-3}$ eV$^2$/c$^4$.

For the T2K anti-$\nu_e$ appearance search we detected 3 events when 1.3 events are expected in case of no oscillation. 3.7 events are expected if anti-neutrinos oscillate with the same parameters as neutrinos assuming normal mass hierarchy and $\delta_{CP}=-\pi/2$ (see the left plot of Fig.3 for the energy distribution of those events). The expected number of events depends on $\delta_{CP}$ phase and the mass hierarchy. For the normal mass hierarchy, we expect 3.7, 4.3 and 4.9 events for $\delta_{CP}$ equals $-\pi/2$, 0 and $\pi/2$.
\( \pi/2 \) respectively. For the inverted mass hierarchy, those numbers change to 4.2, 4.9 and 5.5 expected events. Since the statistics of anti-\( \nu \) accumulated data is low, we introduce the \( \beta \) parameter which rescales the probability of anti-\( \nu_e \) appearance:

\[
P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) = \beta \times P_{\text{PMNS}}(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)
\]

\( \beta=0 \) corresponds to the situation when no anti-\( \nu_e \) oscillation occurs while \( \beta=1 \) represents the case where anti-\( \nu_e \) appearance occurs with the same oscillation parameters as \( \nu_e \) appearance. Toy experiments were performed which throw parameters \( q_{23}^2, q_{13}, D_{m_{32}}^2 \) and \( \delta_{CP} \) to obtain the expected number of events for each toy MC for two values of parameter \( \beta \) (0 or 1). The obtained distribution of the expected number of events for those two scenarios is shown in right plot of Fig.3. This shows that, with only 3 detected events, those two scenarios can not be distinguished. More statistics are required to judge whether anti-\( \nu_e \rightarrow \text{anti-} \nu_e \) oscillation occurs.

6. Summary remarks
T2K is a world-leading experiment of neutrino physics, which has provided the most precise measurement of the \( \theta_{23} \) mixing angle and discovered the appearance of \( \nu_e \) in \( \nu_\mu \) beam. We have also started to be sensitive to the unknown \( \delta_{CP} \) violating phase, and to exclude some of its values when we combine our results with these from reactor neutrino experiments. T2K has begun to analyze its anti-\( \nu_\mu \) disappearance, and has proven that anti-\( \nu_\mu \) disappearance is consistent with neutrino results. Results based on statistics discussed here are insufficient to allow us to draw conclusions regarding anti-\( \nu_e \) appearance. For the most up-to-date situation, the reader may refer to the results announced during Neutrino 2016 and ICHEP 2016 conferences.

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