STATUS AND PROSPECTS OF NEUTRINO OSCILLATIONS*

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(Received November 14, 2017)

Last two decades have shown big progress in understanding of neutrino physics. Such phenomena as oscillations have been proved to exist by solar and atmospheric neutrino experiments. Later, some of those results have been confirmed by the accelerator experiments which use the muon neutrino beam produced from interaction of protons on the target. Last years gave us exciting results of observation of appearance of electron neutrinos as well as first measurements with anti-neutrino beam. This publication presents overview of current oscillation results and future plans as well for accelerator experiments as for solar neutrino projects or reactor experiments.

DOI:10.5506/APhysPolB.48.2203

1. Introduction

Phenomenon of neutrino oscillations was first discovered in 1998 by the Super-Kamiokande experiment [1]. At that time, it was proved that muon neutrinos produced in the atmosphere transform spontaneously its flavor when traveling through the Earth. The results were interpreted as oscillation of muon neutrinos to tau neutrinos, $\nu_\mu \to \nu_\tau$. Few years later, in 2001, the solar neutrino puzzle was resolved by the SNO experiment [2]. SNO proved that electron neutrinos produced in the Sun change its flavor when traversing through the matter of the Sun. For those two discoveries, the 2015 Nobel Price was awarded to prof. Taakaki Kajita from University of Tokyo and prof. Arthur B. McDonald form Queens's University.

The neutrino oscillations phenomenon is a consequence of the fact that neutrino mass eigenstates (ν_1, ν_2, ν_3) are not identical to the neutrino flavor states $(\nu_e, \nu_\mu, \nu_\tau)$, but they can be described by the Pontecorvo–Maki–Nakagawa–Sakata mixing matrix as given by Fig. 1. So far, all of the mixing

* Presented at the XLI International Conference of Theoretical Physics "Matter to the Deepest", Podlesice, Poland, September 3–8, 2017.

$$U=\begin{pmatrix}1 & 0 & 0\\ 0 & \cos\theta_{23} & \sin\theta_{23}\\ 0 & -\sin\theta_{23} & \cos\theta_{23}\end{pmatrix}\begin{pmatrix}\cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta_{\rm CP}}\\ 0 & 1 & 0\\ -\sin\theta_{13}e^{i\delta_{\rm CP}} & 0 & \cos\theta_{13}\end{pmatrix}\begin{pmatrix}\cos_{12} & \sin\theta_{12} & 0\\ -\sin\theta_{12} & \cos\theta_{12} & 0\\ 0 & 0 & 1\end{pmatrix}$$

Fig. 1. Pontecorvo–Maki–Nakagawa–Sakata mixing matrix.

angles and mass square differences have already been measured by various experiments (see Table I for summary). The θ_{12} and Δm^2_{21} are probed by the solar neutrino experiments (such as SNO or Borexino), Super-Kamiokande together with accelerator experiments (K2K, MINOS, OPERA, T2K, NOvA) measuring the atmospheric neutrino parameters θ_{23} and $|\Delta m^2_{32}|$, while the most precise measurement of the third mixing angle, θ_{13}, was provided by the reactor experiments (Daya Bay, Double Chooz, RENO).

TABLE I

Current values of measured neutrino oscillation parameters [3].

Parameter	Value
θ_{12}	$33.4 \pm 0.85°$
Δm^2_{21}	$(7.53 \pm 0.18) \times 10^{-5}$ eV^2
θ_{23}	$45.8 \pm 3.2°$
$\left\|\Delta m^2_{32}\right\|$	$(2.44 \pm 0.06) \times 10^{-3}$ eV^2
θ_{13}	$8.88 \pm 0.39°$

A lot of questions still remain open in neutrino physics. Current and future experiments will try to determine if θ_{23} mixing angle is maximal or not. We are still not sure if CP is conserved or violated in the neutrino sector. Additionally, neither neutrino mass ordering nor absolute values of neutrino masses are known.

2. Neutrino oscillations by accelerator experiments

2.1. Overview

The next step after discovery of neutrino oscillations using natural sources of neutrinos was to confirm this process under controlled beam conditions. In consequence, the first long baseline neutrino oscillation experiment was designed — K2K (1999–2004). Using the KEK accelerator, it collided protons with graphite target producing secondary particles such as charged pions and kaons. By using magnetic horn, positively charged pions were selected giving origin to almost pure muon neutrino beam. This scheme of producing muon neutrino beam has been used for all accelerator neutrino experiments later on. The K2K experiment indeed confirmed that muon neutrinos disappear [4], by observing so-called $\nu_\mu \to \nu_\mu$ oscillations, in agreement with oscillation parameters derived from measurement of atmospheric neutrinos. Later on, the MINOS experiment (2005–2016) provided more precise measurement of neutrino oscillations from atmospheric neutrino sector [5]. On the other hand, the OPERA experiment (2008–2012) by direct observation of ν_τ interactions [6] proved that muon neutrinos are indeed transformed into taon neutrinos. Search of $\nu_\mu \to \nu_e$ oscillations, started originally by K2K, became the first goal of the next T2K experiment. T2K has been taking data from 2009 and so far performed analysis of muon neutrino disappearance and electron neutrino appearance using neutrino and anti-neutrino beams [7]. Similar program has been realized by the NOvA experiment, which started its operation in 2014. The following sections will summarize latest results of the currently running neutrino accelerator experiments as T2K and NOvA and discuss prospects for the future projects.

2.2. Results of T2K experiment

The T2K experiment was designed to proceed with the accelerator neutrino program originally started by the first neutrino oscillation experiment with long baseline K2K located in Japan. Contrary to K2K, it uses the JPARC accelerator located in Tokay, not in the KEK. In this experiment, 30 GeV proton beam hits graphite target producing neutrinos of the mean energy of 700 MeV. The T2K experiment collected data in neutrino and anti-neutrino mode, accumulating 1.49×10^{21} POT and 0.76×10^{21} POT, respectively, for neutrinos and anti-neutrinos. Such produced a neutrino beam crosses the near-detector system placed 280 meters from the production target where unoscillated neutrino beam is studied providing us with precise measurements of neutrino interaction cross sections and flux measurement. The beam is directed towards the far detector Super-Kamiokande located 295 km away from the production point. Using the far-detector data correlated with the beam from JPARC, the neutrino oscillations are measured. Since the Super-Kamiokande detector can distinguish between neutrino interactions originated by ν_μ and ν_e, then analyses for ν_μ-disappearance and ν_e-appearance are performed. One of the interesting things was to check whether transformation of $\bar{\nu}_\mu \to \bar{\nu}_\mu$ is driven by the same oscillation parameters as transformation of $\nu_\mu \to \nu_\mu$, or saying it in different way whether CPT is conserved in the neutrino sector. Such analyses using muon neutrino-induced events for neutrino and anti-neutrino beams were performed. The disappearance of muon neutrinos was observed as well for neutrino as for anti-neutrino run [8]. The allowed region of oscillation parameters is shown in the left plot of Fig. 2 showing that results from anti-neutrino oscillation are consistent with those from neutrino run of T2K as well as with Super-Kamiokande atmospheric neutrino and MINOS beam neutrino results.

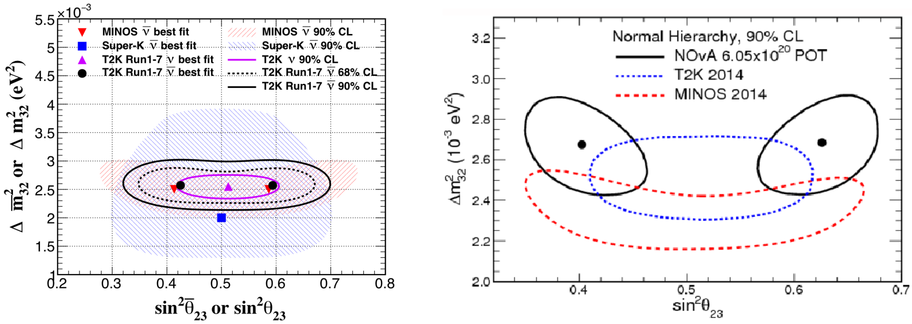

Fig. 2. Left: Allowed region of atmospheric parameters for neutrino (θ_{23}, Δm^2_{32}) and anti-neutrino ($\bar{\theta}_{23}$, $\Delta \bar{m}^2_{32}$) run in T2K experiment. Right: Allowed region of neutrino oscillation parameters measured by NOvA experiment with comparison to MINOS and T2K results.

In 2011, the T2K announced discovery of the $\nu_\mu \to \nu_e$ oscillations as the first experiment in the world [9]. This process is driven by the θ_{13} mixing angle, whose value measured by T2K is consistent with the most precise measurement of the mixing angle provided by the reactor experiments. It is important to point out that this process is crucial for the search of the CP violation in neutrino sector. The presence of the CP violation process should be manifested in asymmetry of oscillations of $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$. Both of those processes were observed in measurements of neutrino and anti-neutrino beam in T2K. The summary of number of observed events for neutrino and anti-neutrino run is presented in Table II together with the predicted number of events for different scenarios depending on value of the $\delta_{\rm CP}$-violating phase (see Fig. 1). Values of $\delta_{\rm CP}$ equal 0 or π corresponding to the CP conserving scenarios. As can be seen from Table II, the number of observed events for neutrino run is larger than expectation for no CP violation scenarios in contrary to anti-neutrino run when the number of observed events is smaller than predicted for $\delta_{\rm CP} = 0$ or π. The observed number of events seams to be consistent with predictions for $\delta_{\rm CP} = 0.5\pi$. The oscillation analyses were performed and the allowed region of oscillation

TABLE II

The number of expected events for various scenarios of $\delta_{\rm CP}$-violating phase and number of events collected for analyzed data sample.

	$\delta_{\rm CP} = -0.5\pi$	$\delta_{\rm CP} = 0$	$\delta_{\rm CP} = 0.5\pi$	$\delta_{\rm CP} = \pi$	Observed
ν_e CCQE	73.5	61.5	49.9	62.0	74
$\bar{\nu}_e$ CCQE	7.93	9.04	10.04	8.93	7

parameters was obtained pointing to $\sin^2\theta_{13} = 0.0277^{+0.0054}_{-0.0047}$. The obtained 2σ intervals for $\delta_{\rm CP}$ are $[-2.98, -0.60]$ and $[-1.54, -1.19]$ for normal and inverted hierarchy respectively. Therefore, as can be seen from Fig. 3, the CP conserving values are outside of 2σ intervals.

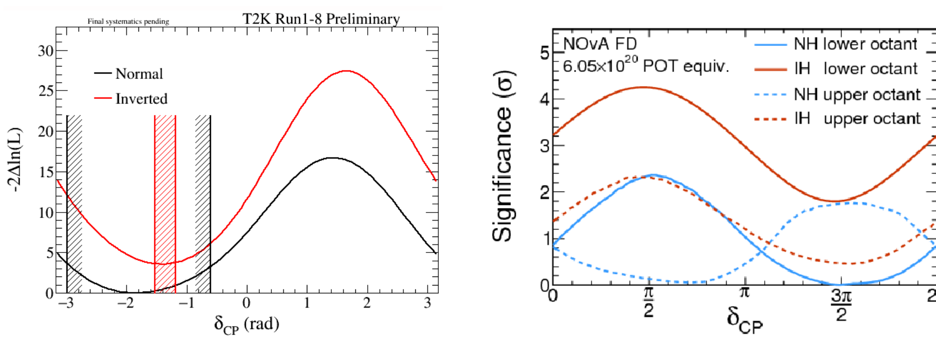

Fig. 3. Left: 2σ confidence intervals for the measured χ^2 distributions for the T2K experiment. Right: Significance for $\delta_{\rm CP}$ derived by the NOvA experiment.

2.3. Results of NOvA experiment

The NOvA experiment studies neutrinos from NuMi beam at Fermilab. It produces neutrinos of the mean energy of 2 GeV and send the beam 810 km away for its interaction to be detected in the scintillating detector located in Ash River. It also uses near detector which provides reference measurement of unoscillated neutrino spectrum for oscillation analysis. So far, the NOvA experiment collected 8.79×10^{20} POT of neutrino data. Their results of $\nu_\mu \to \nu_\mu$ disappearance oscillation excluded maximal value of θ_{23} mixing angle at 2.6σ level [10]. The allowed region of oscillation parameters is shown in the right plot of Fig. 2. Allowed regions are consistent with T2K and MINOS results, however, the best fit points lay outside of allowed regions for measurements of those two experiments. The NOvA experiment also detected access of ν_e events (33 events observed with 8.2 ± 0.8 events expected in the case of no oscillation) and performed the joint fit of ν_μ and ν_e data [11]. The obtained significance for $\delta_{\rm CP}$ is presented in the right plot of Fig. 3. It favors the value of $\delta_{\rm CP}$ $3\pi/2$ which is consistent with the T2K observation.

2.4. Future of long baseline experiment

The next step of both experiments, NOvA and T2K, would be to precisely measure probabilities of oscillation for $\bar{\nu}_\mu \to \bar{\nu}_e$ and $\nu_\mu \to \nu_e$. This measurement is also sensitive to the value of θ_{23} mixing angle (is it maximal or not), to mass hierarchy, and to value of $\delta_{\rm CP}$-violation phase. Recently, in February 2017, NOvA switched to $\bar{\nu}$ mode and plans to collect ν and $\bar{\nu}$ data in 2018. It expects to obtain 3σ sensitivity to maximal mixing of θ_{23} in 2018. In 2024, it plans to achieve 2–3σ sensitivity to $\delta_{\rm CP}$.

In 2017 and 2018, T2K is planning to accumulate 0.8×10^{21} POT. It is also waiting for upcoming upgrade of Main Ring power which will allow to produce more intense neutrino beams; T2K proposed to extent its operation to 2025 and accumulate 20×10^{21} POT reaching 3σ sensitivity to $\delta_{\rm CP}$.

The long-term plans are related to design two new long baseline experiments: DUNE in USA [12] and Hyper-Kamiokande in Japan [13]. The first one will produce a wide-band neutrino beam of energy of few GeV and send neutrinos on 1300 km distance, while the second one plans to use narrow band beam with mean energy of 600 MeV and study neutrino oscillation on 295 km distance. The Hyper-Kamiokande plans to build huge water Cherenkov detector using the same technique as Super-Kamiokande but with 10 times larger active volume. DUNE is designing 40 kT liquid argon time projection chamber. Both experiments are scheduled to start its operation in 2026. The physics plan of those two experiment is similar, for both of them, the main target would be discovery of CP violation in the neutrino sector. They are planning to perform precise measurements of other oscillation parameters and determine mass hierarchy — here DUNE may play more important role thanks to its longer baseline. On top of it, they may perform neutrino astrophysics measurements and search for proton decay or dark matter.

3. Solar neutrino oscillations

The oscillation of solar neutrinos was proved by the SNO experiment which was sensitive to various types of neutrino interactions. By measuring charged current processes, it measured electron neutrino flux which was about 35% of that predicted by the Standard Solar Model. On the contrary, when measuring neutral current processes sensitive to all neutrino flavors, it measured the flux consistent with predictions. Therefore, the original ν_e of energy of about 10 MeV (^8B solar neutrino flux) undergos matter oscillation in the Sun. Later on, the Borexino experiment measured oscillations of solar neutrinos, but for different neutrino energies (so-called *pep*, ^{7}Be and *pp* flux) reaching down to 300 MeV energy of produced ν_e in the Sun [14]. Obtained results are consistent with Large Mixing Angle prediction and prove oscillations of solar neutrinos. The summary of analysis of solar neutrino sector is presented in Fig. 4, where the allowed region of Δm^2_{21} and $\sin^2\theta_{12}$ is shown. On top of it, results of KamLAND reactor experiment are also presented [15]. This experiment studied disappearance of reactor produced

$\bar{\nu}_e$ at the distance of hundred kilometers, what makes it sensitive to solar neutrino oscillation parameters. The results of KamLAND suggest larger Δm^2_{21}, then the global fit to solar data.

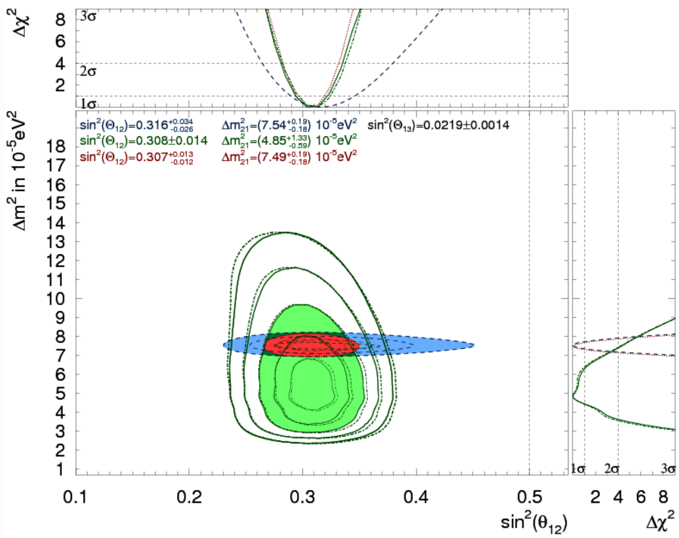

Fig. 4. (Color online) Comparison of oscillation parameters derived by solar neutrino data (lighter gray/green) with KamLAND data (darker gray/blue).

The possible explanation may lay in the observed Day–Night effect by the modular observation of solar ν_e by the Super-Kamiokande detector. Results show that the detected flux is different for neutrinos detected at day time from those detected at night time: $\frac{(\mathrm{Day}-\mathrm{Night})}{(\mathrm{Day}+\mathrm{Night})/2} = -3.3 \pm 1.0(\mathrm{stat.}) \pm 0.5(\mathrm{syst.})$. This 2.9σ effect can be interpreted as recovery of ν_e while traversing the Earth diameter at night time.

4. Studying neutrinos with reactor experiments

One of the most important measurements in neutrino physics in last years is related to reactor experiments such as Daya Bay, Double Choos and RENO [16]. All of those experiments study disappearance of $\bar{\nu}_e$ produced by reactor power plants at the distance up to 1 km. They use near detectors to measure unoscillated neutrino flux and compare it to the flux measured by the far detectors. In consequence, they provided the most precise measurement of the θ_{13} mixing angle. All of those experiments observed the so-called reactor anomaly. When comparing the observed to predicted spectra of prompt positron energy from neutrino interaction, the excess of events is observed around 5 MeV of prompt energy. Although, such excess is seen also in the near-detector data of the RENO experiment what may suggest that this effect is not related to neutrino oscillation phenomena but to modeling of decays of prominent fission daughter isotopes.

The future plan of reactor experiment will be realized by the JUNO and RENO-50 experiments. They plan to probe $\bar{\nu}_e$ oscillations in the L/E region driven by the solar neutrino oscillation parameters. One term of the oscillation probability depends on the sign of the Δm^2_{31} — normal or inverted mass hierarchy, which modifies the oscillation pattern. In such a way, those experiments would like to try determine mass hierarchy.

5. Final remarks

Since discovery of neutrino oscillation two decades ago, a lot of progress has been made in understanding of neutrino oscillations. All oscillation parameters have been measured and currently more effort is put to provide precise measurements of those parameters. New phenomena of CP violation is intensively studied by currently running accelerator experiments and it is going to be the main goal for future long baseline neutrino program. Plans are also made to resolve the mass hierarchy of neutrinos by studying neutrino oscillations in reactor and future accelerator experiments. Current effort is directed towards precise measurements of oscillation parameters what requires to reduce systematic uncertainties of performed oscillation analysis. That requires better understanding of modeling of neutrino interactions with the matter which is intensively studied by near detectors of accelerator experiments, such as T2K, which has already accumulated hundred thousands of neutrino interactions. Additionally, large effort is directed to upgrade the existing near detectors in T2K (learning from current experience) in order to provide more precise measurement of unoscillated neutrino flux. We may expect that the future of neutrino physics will be as exciting as the last decades.

The author acknowledge support of the National Science Centre, Poland (NCN), grant No. 2014/14/M/ST2/00850, and Horizon 2020 MSCA-RISE project JENNIFER, under grant agreement No. 644294.

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