RECENT RESULTS ON THE CP VIOLATION SEARCH IN THE ACCELERATOR NEUTRINO OSCILLATIONS*

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Large value of θ_{13} angle, one of the parameters of neutrino oscillations measured precisely by the reactor experiments, opened a possibility to probe CP-violating phase in neutrino oscillations. The review of the most recent experimental results on the CP violation search in the oscillations of the accelerator neutrinos is presented. Results from the two world-leading long-baseline experiments: T2K and NOvA are discussed. T2K reported its updated results using simultaneous fit to ν_e appearance and ν_μ disappearance channels both for neutrino- and antineutrino-mode beam. T2K provides the 90% C.L. region for $\delta_{\rm CP}$ phase as well as excludes the hypothesis of CP conservation ($\delta_{\rm CP} = 0, \pi$) at 90% confidence level. The article also briefly discusses first results from the NOvA experiment related to the CP phase measurement as well as the prospects for the CP violation search in the planned accelerator neutrino experiments.

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1. Introduction

Neutrinos oscillate which means that they change their flavour from one to another as they travel. This fact was first revealed by the Super-Kamiokande (Super-K) experiment in 1998 [1]. Neutrino oscillations are a quantum-mechanical effect resulting from the fact that the neutrino flavour states which we observe in nature (ν_e, ν_μ, ν_τ) propagate in space as linear combinations of the mass eigenstates: ν_1, ν_2, ν_3. The relation between neutrino flavour states and the mass eigenstates is described by the Pontercorvo–Maki–Nakagawa–Sakata (PMNS) matrix [2]. PMNS matrix can be parametrized using three mixing angles θ_{13}, θ_{23}, θ_{12} and one complex phase $\delta_{\rm CP}$ ($c_{ij} = \cos\theta_{ij}, s_{ij} = \sin\theta_{ij}$).

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The formulas which describe the oscillation probabilities include two more parameters which are the two independent differences of mass squared of the neutrinos: Δm^2_{21}, $\Delta m^2_{32(13)}$. Super-K's discovery made neutrino oscillation physics one of the most dynamically developing areas of research in particle physics. Results from Super-K have been later confirmed and supplemented by many experiments which provided information about mixing angles and mass splittings with a good precision [3].

Most of the mixing parameters have been measured but there are still open questions in the neutrino oscillation physics. Two of the most important questions are: is there a CP violation in the neutrino sector ($\delta_{\mathrm{CP}} \neq 0, \pi$?) and what is the neutrino mass hierarchy related to the sign of $\Delta m^2_{32(13)}$: normal (NH) — $m_3 > m_2 > m_1$ or inverted (IH) — $m_2 > m_1 > m_3$? The question about the CP symmetry violation or conservation in the neutrino sector is a main subject of this article.

2. Accelerator neutrino oscillations

The current long-baseline neutrino experiments study two channels of neutrino oscillations: ν_e appearance in the ν_μ beam and the disappearance of muon neutrinos from the beam. The formula for the ν_e appearance probability which includes the dependence on δ_{CP} phase is particularly important for this article

$$\begin{aligned} P(\nu_\mu \rightarrow \nu_e) \simeq\ & \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\frac{\Delta m^2_{31}L}{4E} \\ & -\frac{\sin 2\theta_{12}\sin 2\theta_{23}}{2\sin\theta_{13}}\sin\frac{\Delta m^2_{21}}{4E}\sin^2 2\theta_{13}\sin^2\frac{\Delta m^2_{31}L}{4E}\sin\delta_{\mathrm{CP}} \\ & +(\mathrm{CP\ term,\ solar\ term,\ matter\ term})\,, \end{aligned} \tag{1}$$

where Δm^2 is either Δm^2_{32} for normal mass hierarchy or Δm^2_{13} for inverted mass hierarchy. In the case of antineutrinos ($P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$), the second term in Eq. (1) has an opposite sign. Two world-leading long-baseline accelerator experiments aiming at the measurements of δ_{CP} using the ν_e appearance channel are described in Sections 3 and 4.

3. The T2K experiment and its results

The first experiment is Tokai to Kamioka (T2K) [4] with $\nu_\mu(\bar{\nu}_\mu)$ beam based on the J-PARC proton accelerator. Neutrinos are sent towards the near-detector station at 280 m and Super-K detector, located 295 km away from J-PARC. T2K uses the off-axis setup with one of the near detectors (ND280) and the far detector located 2.5° away from the beam axis. This setup allows T2K to produce a beam with a narrow energy spectrum peaked at 0.6 GeV which is tuned to maximize the oscillation probability at 295 km. This configuration also minimizes the background in the ν_e ($\bar{\nu}_e$) appearance measurement.

The near-detector station consists of two main parts: the above-mentioned off-axis detector and the on-axis INGRID detector. The goal of the ND280 detector is to measure the neutrino flux before the oscillation occurs and provide the information about the instrinsic ν_e contamination in the beam, as well as measure various neutrino cross sections. The INGRID detector monitors the beam rate, direction and stability, and measures various neutrino cross sections [4]. The far detector of the T2K experiment (Super-K) is the world's largest land-based water Cherenkov detector which has been operating since 1996 and which technology and operations are well-understood [5].

The T2K analysis described in this article is based on the exposure of 7.482×10^{20} protons on target (POT) in neutrino mode and 7.471×10^{20} POT in antineutrino mode collected at T2K far detector during seven physics runs (January 2010–May 2016) [6]. The oscillation parameters are estimated by comparing predictions and observations at the far detector. A tuned prediction of the oscillated neutrino spectrum at the far detector, with associated uncertainty, is obtained by fitting samples of charged-current neutrino interactions at ND280. The oscillation parameters are estimated by performing a joint maximum-likelihood fit of the far detector samples using PMNS neutrino oscillation model.

Moreover, in T2K, there are three analyses using different statistical approaches and different far detector data quantities in order to cross-check results. All three independent analyses are in a good agreement.

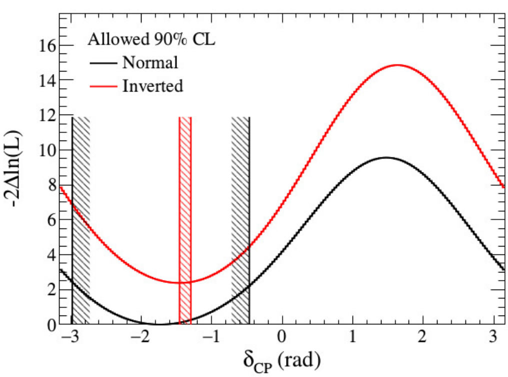

Fig. 1. One-dimensional $\Delta\chi^2$ surfaces for oscillation parameter $\delta_{\rm CP}$ using T2K data with the reactor constraint on θ_{13}. The critical $\Delta\chi^2$ values were obtained with the Feldman–Cousins method [6].

The final results, with the additional constrain on θ_{13} angle from reactor experiments [3], are shown in Fig. 1. The 90% confidence region for $\delta_{\rm CP}$ phase is estimated to be: $[-2.95, -0.44]$ ($[-1.47, -1.27]$) for normal (inverted) mass ordering. The hypothesis of CP symmetry conservation ($\delta_{\rm CP} = 0, \pi$) is excluded at 90% confidence level. T2K has a preference for $\delta_{\rm CP} = -\pi/2$.

4. The NOvA experiment and its results

NOvA is a long-baseline neutrino experiment which is optimized to study the oscillation of muon neutrinos to electron neutrinos [7]. The experiment uses a 14 kt liquid scintillator Far Detector (FD) in Ash River, Minnesota to detect the oscillated muon neutrino beam (NuMI) produced 810 km away at Fermilab. NOvA has a smaller (0.3 kt), functionally identical Near Detector (ND) located at Fermilab to measure the properties of unoscillated beam neutrinos and estimate backgrounds at the far detector. Both detectors are located 14.6 mrad ($\approx 0.8^\circ$) off-axis to achieve a narrow-band neutrino energy spectrum near the energy of 2 GeV corresponding to the maximum in the $\nu_\mu \to \nu_e$ oscillations in the FD.

NOvA experiment recently reported the constraints on oscillation parameters from the first combined fit of ν_e appearance and ν_μ disappearance data [7]. The data analysed were collected between February 2014 and May 2016. The exposure is equivalent to 6.05×10^{20} protons on target (POT).

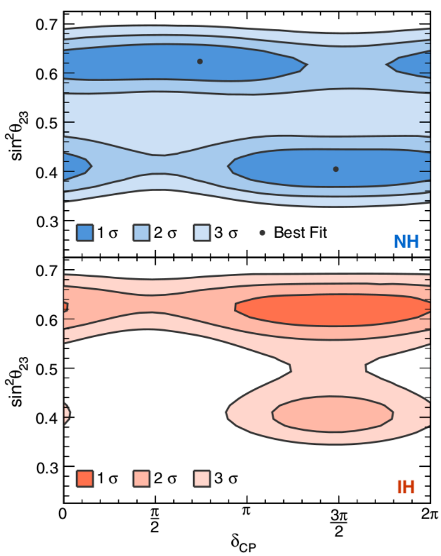

Fig. 2. Allowed regions in $\delta_{\rm CP}$–$\sin^2\theta_{23}$ plane from the NOvA experiment. The top plot corresponds to the normal mass hierarchy, while the bottom one to the inverted hierarchy. 1, 2, 3σ C.L. allowed regions are shown with different colours [7].

A sample of ν_μ candidates are selected in the ND data and their true energy spectrum is estimated. The spectrum of true ν_e CC signal events selected in the FD simulation is corrected by the ratio of the ν_μ CC true energy spectrum derived from ND data to the simulated ν_μ CC spectrum. The adjusted FD signal spectrum is weighted by the ν_e appearance probability and mapped to the reconstructed energy spectrum for the final estimate of the ν_e appearance signal. To extract oscillation parameters, the FD ν_e and ν_μ CC energy spectrum are fit simultaneously.

The results of the fit are shown in Fig. 2. NOvA reports two degenerate best-fit points in the normal hierarchy: $\sin^2\theta_{23} = 0.404$, $\delta_{\mathrm{CP}} = 1.48\pi$ and $\sin^2\theta_{23} = 0.623$, $\delta_{\mathrm{CP}} = 0.74\pi$. The best-fit point in the inverted hierarchy occurs near $\delta_{\mathrm{CP}} = 3\pi/2$ $(-\pi/2)$. It is necessary to stress that the T2K's best fit value for $\sin^2\theta_{23}$ is not degenerate and is very close to 0.5. Although NOvA reported the θ_{23} degeneracy, its results on δ_{CP} are consistent with T2K.

5. Future perspectives

Both T2K and NOvA should be operating until 2024–2026. NOvA will be constantly taking data up to 2024 and should be able to reach $\sim 2\sigma$ significance to disfavour CP conservation hypothesis [8]. The T2K experiment will upgrade the beam and near detectors, and start data-taking with this upgraded setup in 2021. The projected amount of data to be taken by T2K by 2026 is 20×10^{21} POT and the sensitivity to exclude $\sin\delta_{\mathrm{CP}} = 0$ should be greater than 3σ [9].

The important thing to notice is that both T2K and NOvA have only the 'indication potential' for the CP violation search and they will not be able to measure the value of δ_{CP} with a 5σ significance. In order to perform a measurement of the CP phase, the next generation experiments are needed. In the perspective of the next ten years, two major projects are considered: Hyper-Kamiokande (Japan) and DUNE (USA).

Hyper-Kamiokande will be the continuation of the T2K experiment with the neutrino beam upgraded ultimately to 1.3 MW and the far detector containing ~ 500 kt of water doped with gadolinium built in the similar technology as Super-K. Hyper-Kamiokande should start data-taking in 2026, and its goal is to reach the uncertainty on δ_{CP} as low as 7–21 degrees after 10 years of running [10].

DUNE is the US flagship project which is expected to launch in 2025. The experiment will use a neutrino beam produced in Fermilab which will be sent towards the far detector located 1300 km away in the Sanford Underground Research Facility (SURF) in South Dakota. The far detector is expected to have 40 kt of fiducial mass and will be built in liquid argon time projection chamber technology (single or double phase). The expected δ_{CP} resolution after 10 years of detector exposure should reach 6–10 degrees [11].

6. Summary

T2K and NOvA experiments reported their results on the $\delta_{\rm CP}$ phase measurement. The first constrains on $\delta_{\rm CP}$ at 90% C.L. are provided by T2K with the preference for the maximal CP violation ($\delta_{\rm CP} = -\pi/2$). NOvA and upgraded T2K should be able to exclude $\sin\delta_{\rm CP} = 0$ with $\sim 3\sigma$ significance by 2025. The future experiments: DUNE and Hyper-K (start $\sim$ 2025) are expected to measure $\delta_{\rm CP}$ with the resolution of 6–21 degrees.

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