PRAMANA
— journal of
physics

© Indian Academy of Sciences

Vol. 86, No. 2
February 2016
pp. 387–393

Evidence for leptonic CP phase from NOνA, T2K and ICAL

MONOJIT GHOSH[1,*], POMITA GHOSHAL[2], SRUBABATI GOSWAMI[1]
and SUSHANT K RAUT[3]

[1]Physical Research Laboratory, Navrangpura, Ahmedabad 380 009, India
[2]Department of Physics, L.N.M. Institute of Information Technology, Rupa-ki-Nangal, post-Sumel, via-Jamdoli, Jaipur 302 031, India
[3]Department of Theoretical Physics, School of Engineering Sciences, KTH Royal Institute of Technology – AlbaNova University Center, Roslagstullsbacken 21, 106 91 Stockholm, Sweden
*Corresponding author. E-mail: monojit@prl.res.in

DOI: 10.1007/s12043-015-1159-5; ***e*Publication:** 13 January 2016

Abstract. The phenomenon of neutrino oscillation is now well understood from the solar, atmospheric, reactor and accelerator neutrino experiments. This oscillation is characterized by a unitary PMNS matrix which is parametrized by three mixing angles (θ_{12}, θ_{23} and θ_{13}) and one phase (δ_{CP}) known as the leptonic CP phase. Neutrino oscillation also involves two mass squared differences: the solar mass square difference ($\Delta_{21} = m_2^2 - m_1^2$) and the atmospheric mass square difference ($\Delta_{31} = |m_3^2 - m_1^2|$). Though there is already significant amount of information about the three mixing angles, the CP phase is still unknown. Apart from the CP phase, one should also know what is the true nature of the neutrino mass hierarchy, i.e., normal ($m_3 > m_1$: NH) or inverted ($m_1 > m_3$: IH) and what is the true octant of θ_{23}, i.e., lower ($\theta_{23} < 45°$: LO) or higher ($\theta_{23} > 45°$: HO). The long-baseline experiments (LBL) have CP sensitivity coming from the appearance channel ($\nu_\mu \rightarrow \nu_e$). On the other hand, atmospheric neutrinos are known to have negligible CP sensitivity. In this work, we study the synergy between the LBL experiment NOνA, T2K and the atmospheric neutrino experiment ICAL@INO for obtaining the first hint of CP violation in the lepton sector. We find that due to the lack of knowledge of hierarchy and octant, CP sensitivity of NOνA/T2K is poorer for some parameter ranges. Addition of ICAL data to T2K and NOνA can exclude these spurious wrong-hierarchy and/or wrong-octant solutions and cause a significant increase in the range of δ_{CP} values for which a hint of CP violation can be achieved. Similarly, the precision with which δ_{CP} can be measured also improves with the inclusion of ICAL data.

Keywords. Neutrino oscillation; leptonic CP phase; long-baseline neutrino experiments; atmospheric neutrino experiments.

PACS No. 14.60.Pg

1. Introduction

CP symmetry implies to invariance under simultaneous transformation of charge conjugation and parity. CP violation has been observed in quark sector and this can be explained by the complex phase of the CKM matrix [1]. Similarly, the complex phase in the leptonic mixing matrix which is analogous to the CKM phase, can lead to CP violation in the lepton sector [2]. However, experiments are needed to detect the CP phase in the leptonic sector to establish this expectation on a firm footing. Determination of the leptonic CP phase is interesting not only for the complete information of the PMNS mixing matrix but also because it can explain the observed matter–antimatter asymmetry of the Universe through the mechanism of leptogenesis [3].

A potential problem in determining δ_{CP} arises from the lack of knowledge of hierarchy and octant which gives rise to fake solutions coming from wrong hierarchy and wrong octant. A prior knowledge of hierarchy and octant can help to eliminate these fake solutions thereby enhancing the CP sensitivity. As the baselines of the current superbeam experiments T2K and NOνA are not too large, they have limited hierarchy and octant sensitivity, thus causing a significant fall in the CP sensitivity. On the other hand, the hierarchy and octant sensitivity of atmospheric neutrino experiments are independent of δ_{CP} [4]. Hence, a combination of long-baseline (LBL) and atmospheric data can substantially improve the ability of the LBL experiments to measure δ_{CP}. In this work, we demonstrate that the CP sensitivity of T2K and NOνA can be enhanced significantly by including atmospheric neutrino data in the analysis. For the latter we consider a magnetized iron calorimeter detector (ICAL) which is being developed by the INO Collaboration [5].

2. The appearance channel

In matter of constant density, $P_{\mu e}$ can be expressed in terms of the small parameters $\alpha = \Delta_{21}/\Delta_{31}$ and s_{13} as [6]

$$P_{\mu e} = 4s_{13}^2 s_{23}^2 \frac{\sin^2[(1-\hat{A})\Delta]}{(1-\hat{A})^2} + \alpha \sin 2\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \cos(\Delta - \delta_{\mathrm{CP}}) \times \frac{\sin \hat{A}\Delta}{\hat{A}} \frac{\sin[(1-\hat{A})\Delta]}{(1-\hat{A})} + \mathcal{O}(\alpha^2), \quad (1)$$

where $\Delta = \Delta_{31}L/4E$, $s_{ij}(c_{ij}) \equiv \sin\theta_{ij}(\cos\theta_{ij})$, $\hat{A} = 2\sqrt{2}G_{\mathrm{F}}n_e E/\Delta_{31}$, G_{F} is the Fermi constant and n_e is the electron number density. For neutrinos, the signs of $\hat{A}$ and Δ are positive for NH and negative for IH and vice versa for antineutrinos. We can see that CP appears in the subleading second term in eq. (1), which is also the source of the hierarchy-δ_{CP} degeneracy [7].

3. Experimental specification

For the long-baseline experiments NOνA and T2K, simulation is done using the GLoBES package [8]. T2K ($L = 295$ km) is assumed to have a 22.5 kt water Čerenkov detector running effectively for $5(\nu) + 0(\bar{\nu})$ years. For NOνA ($L = 812$ km), we consider a 14 kt TASD detector running for $5(\nu)+5(\bar{\nu})$ years. Detailed specifications of these experiments are given in [9,10].

For atmospheric neutrinos, we consider ICAL@INO, which is capable of detecting muon events with charge identification, with a proposed mass of 50 kt [5]. For our analysis, we use neutrino energy and angular resolutions of 10% and 10°.

4. CPV discovery potential of NOνA, T2K and ICAL

The discovery potential of an experiment for CP violation is defined by

$$\chi^2 = \min \frac{(N_{\mathrm{ex}}(\delta_{\mathrm{CP}}^{\mathrm{tr}}) - N_{\mathrm{th}}(\delta_{\mathrm{CP}}^{\mathrm{test}} = 0, 180°))^2}{N_{\mathrm{ex}}(\delta_{\mathrm{CP}}^{\mathrm{tr}})}, \tag{2}$$

where N_{ex} and N_{th} are the true and test events respectively.

From the upper panels of figure 1, it may be observed that the CPV discovery of NOνA+T2K suffers a drop in the region $+90°$ if it is NH and $-90°$ if it is IH. This is due to the fact that the χ^2 minimum for CPV discovery occurs in the wrong hierarchy. For atmospheric neutrinos, the baselines are related to the zenith angle θ_z. As δ_{CP} always

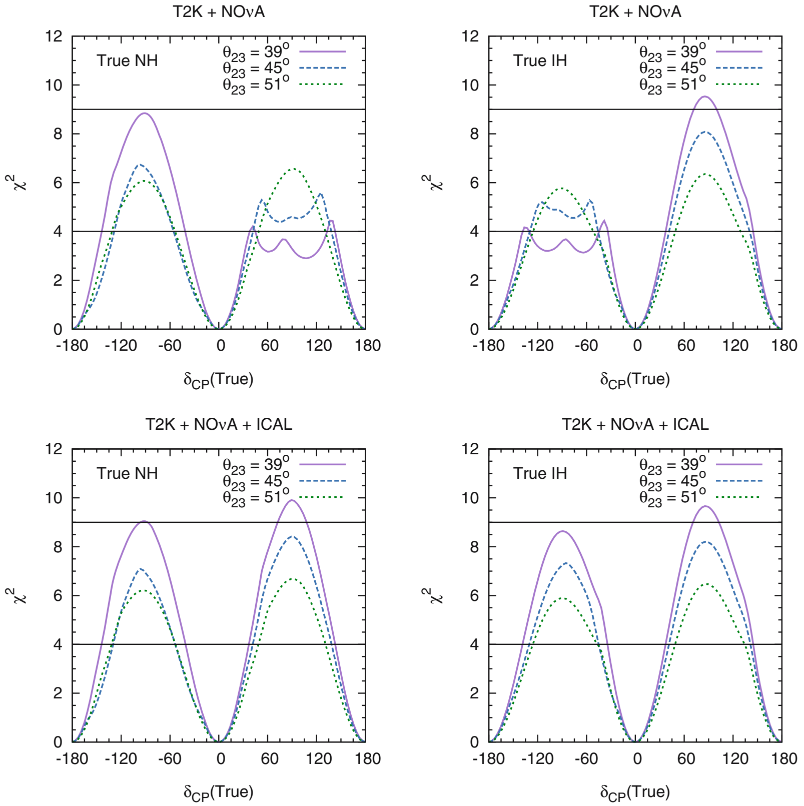


Figure 1. CPV discovery vs. true δ_{CP} for NOνA+T2K (upper row) and NOνA+T2K +ICAL (lower row), for three values of θ_{23}, $\sin^2 2\theta_{13} = 0.1$ and a true normal (left panels) or inverted (right panels) mass hierarchy, with 500 kt yr exposure for ICAL.

appears along with a factor of cos Δ or sin Δ, even for a 10% error range in θ_z this oscillating term varies over an entire cycle. As a result, the δ_{CP}-sensitivity gets washed out. Thus, atmospheric neutrino experiments by themselves are not sensitive to δ_{CP} but gives a hierarchy sensitivity due to large matter effect. This hierarchy sensitivity can exclude the wrong-hierarchy solutions. It is shown in lower panels of figure 1 that when ICAL is added to NOνA+T2K, the drop in the CPV discovery is resolved. The results depend significantly on the true value of θ_{23}. As θ_{23} increases, hierarchy sensitivity increases but CP sensitivity decreases. As a result, for $\theta_{23} = 51°$, the χ^2 minima for NOνA+T2K comes in the correct hierarchy and the ICAL information becomes superfluous.

5. CP precision of NOνA, T2K and ICAL

The precision χ^2 is defined as

$$\chi^2 = \min \frac{(N_{\mathrm{ex}}(\delta_{\mathrm{CP}}^{\mathrm{tr}}) - N_{\mathrm{th}}(\delta_{\mathrm{CP}}^{\mathrm{test}}))^2}{N_{\mathrm{ex}}(\delta_{\mathrm{CP}}^{\mathrm{tr}})}. \tag{3}$$

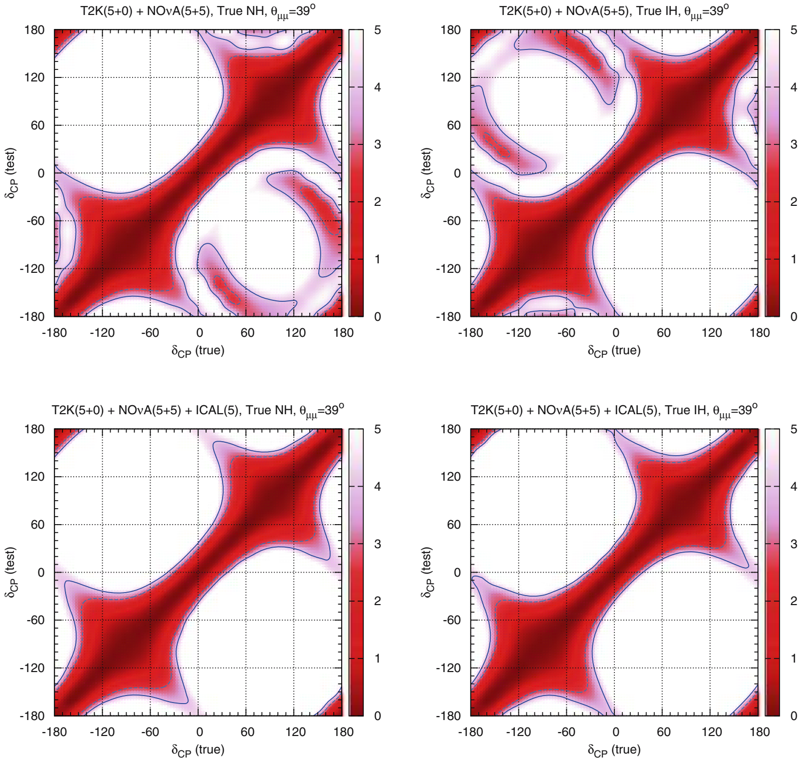


Figure 2. CP precision at 90%/95% CL for NOνA+T2K (upper row) and NOνA+T2K+ICAL (lower row), for $\theta_{23} = 39°$, $\sin^2 2\theta_{13} = 0.1$ and a true normal (left panels) or inverted (right panels) mass hierarchy, with 250 kt yr exposure for ICAL.

In figure 2, we plot the CP precision in δ_{CP}(true) vs. δ_{CP}(test) plane for NOνA, T2K and ICAL. In this figures, we have used $\sin\theta_{23} = \sin\theta_{\mu\mu}/\cos\theta_{13}$, to take care of the intrinsic octant degeneracy that arises at $\theta_{\mu\mu}$ and $90° - \theta_{\mu\mu}$ in the disappearance channel.

The allowed values of δ_{CP} are represented by the shaded regions. For ideal measurement, the allowed values would be very close to the true value. However, due to the hierarchy-δ_{CP} degeneracy, we see that for NOνA+T2K, other δ_{CP} values are also allowed (upper panels of figure 2). However, the addition of five years of ICAL data is sufficient to rule out those degenerate allowed regions at 2σ to give a finer CP precision (lower panels of figure 2), though it should be noted that the act of adding ICAL data does not help in the diagonal regions.

6. θ_{13} and θ_{23} dependence in CPV discovery χ^2

As seen in eq. (1), $P_{\mu e}$ has a leading order CP-dependent term $\sim\sin^2\theta_{13}\sin^2\theta_{23}$ and a subleading CP-independent term $\sim\sin 2\theta_{13}\sin 2\theta_{23}$. Thus, θ_{13} and θ_{23} are expected to have similar dependence on δ_{CP}.

For illustrative purposes, the CP χ^2 can be written as

$$\chi^2 \sim \frac{P(\delta_{\mathrm{CP}})\sin^2 2\theta_{i3}}{Q\sin^2\theta_{i3} + R(\delta_{\mathrm{CP}})\sin 2\theta_{i3}}, \tag{4}$$

where P, Q and R are functions of the other oscillation parameters apart from δ_{CP} and $i = 1, 2$. For small values of θ_{i3}, $\chi^2 \sim \theta_{13}$ which is an increasing function and when θ_{13} is close to 90°, $\chi^2 \sim (90° - \theta_{13})^2$ which decreases with θ_{13}. Therefore, CP sensitivity initially increases with θ_{i3}, peaks at an optimal value, and then decreases with θ_{i3}.

These features are clearly reflected in figure 3. The left panel shows that sensitivity to CP violation is maximum for NOνA+T2K in the current 3σ range of θ_{13} (region between the vertical black lines). From the right panel, we find that for $40° < \theta_{\mu\mu}^{\mathrm{tr}} < 49°$, there is a wiggle signalling the octant-δ_{CP} degeneracy. The behaviour is different for $\delta_{\mathrm{CP}}^{\mathrm{tr}} = \pm 90°$ depending on the true octant.

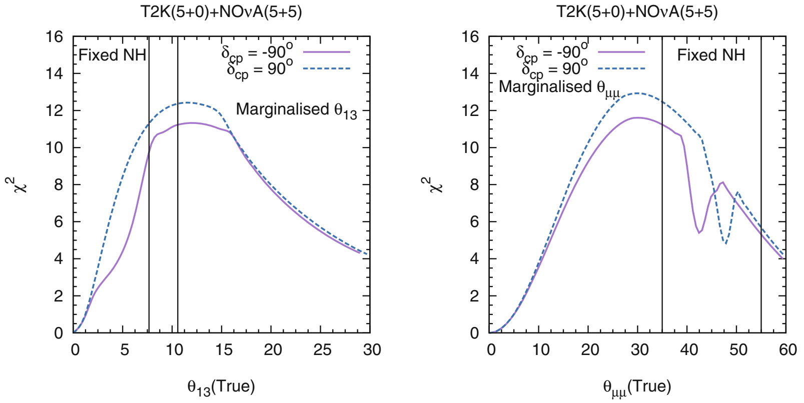
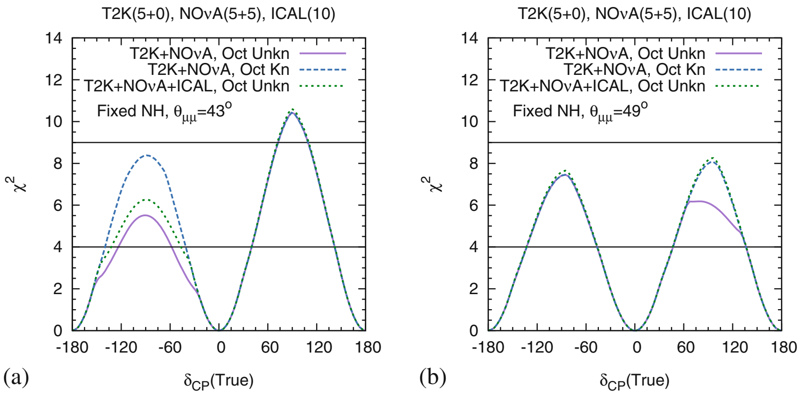


Figure 3. CP violation discovery potential of NOνA+T2K as a function of true θ_{i3}. NH is fixed.



(a) (b)

Figure 4. CP violation discovery potential of NOνA, T2K and ICAL as a function of true $\delta_{\rm CP}$ for (**a**) $\theta_{\mu\mu}^{\rm tr} = 43°$ and (**b**) 49°. $\sin^2 2\theta_{13}^{\rm tr} = 0.1$ and NH is fixed.

This is illustrated in figure 4, where we can notice a drop at $-90°$ for $\theta_{\mu\mu} = 43°$ and at $+90°$ for $\theta_{\mu\mu} = 49°$ for NOνA+T2K, when the octant is assumed to be unknown. But when ICAL is added, it restricts the $\delta_{\rm CP}$-octant degeneracy to $41° < \theta_{\mu\mu} < 48°$. Thus, we can see a partial improvement at $\theta_{\mu\mu} = 43°$ but the degeneracy is fully resolved at $\theta_{\mu\mu} = 49°$ with the help of ICAL.

7. Conclusion

In this work we have studied CP sensitivity of the current and upcoming long-baseline experiments T2K and NOνA and the atmospheric neutrino experiment ICAL@INO. We see that due to hierarchy-$\delta_{\rm CP}$ degeneracy, there is a drop in CP sensitivity for NOνA and T2K in the degenerate region. The main role of the atmospheric neutrino data is to exclude wrong hierarchy solutions to lift the degeneracy in the unfavourable parameter regions for T2K/NOνA. We have also shown that the current values of θ_{13} lies in a region where CP sensitivity is maximum. There is also a degeneracy of $\delta_{\rm CP}$ with the octant in the range $40° < \theta_{\mu\mu}^{\rm tr} < 49°$ for T2K+NOνA. Addition of ICAL data helps to restrict the degeneracy at $41° < \theta_{\mu\mu}^{\rm tr} < 48°$. We note that the idea discussed in this paper can be of importance and interest to other atmospheric and/or reactor experiments (for example HyperKamiokande [11], PINGU [12], JUNO [13]) sensitive to the mass hierarchy and can initiate similar studies. If those experiments have CP sensitivity of their own, then apart from removing degeneracies they can also help in improving the overall CP sensitivity when added to T2K and NOνA.

More detailed discussions and results can be found in [14,15] on which this article is based.

References

[1] J H Christenson, J W Cronin, V L Fitch and R Turlay, *Phys. Rev. Lett.* **13**, 138 (1964)
[2] G Branco, R G Felipe and F Joaquim, *Rev. Mod. Phys.* **84**, 515 (2012), arXiv:1111.5332

[3] A S Joshipura, E A Paschos and W Rodejohann, *J. High Energy Phys.* **0108**, 029 (2001), hep-ph/0105175

[4] R Gandhi, P Ghoshal, S Goswami, P Mehta, S U Sankar *et al*, *Phys. Rev. D* **76**, 073012 (2007), arXiv:0707.1723

[5] http://www.ino.tifr.res.in

[6] E K Akhmedov, R Johansson, M Lindner, T Ohlsson and T Schwetz, *J. High Energy Phys.* **0404**, 078 (2004), hep-ph/0402175

[7] V Barger, D Marfatia and K Whisnant, *Phys. Rev. D* **65**, 073023 (2002), hep-ph/0112119

[8] P Huber, M Lindner and W Winter, *Comput. Phys. Commun.* **167**, 195 (2005), hep-ph/0407333

[9] T2K Collaboration: Y Itow *et al*, hep-ex/0106019

[10] NOνA Collaboration: D S Ayres *et al*, hep-ex/0503053

[11] K Abe, T Abe, H Aihara, Y Fukuda, Y Hayato, K Huang, A K Ichikawa, M Ikeda *et al*, arXiv:1109.3262 [hep-ex]

[12] IceCube PINGU Collaboration: M G Aartsen *et al*, arXiv:1401.2046 [physics.ins-det]

[13] F Capozzi, E Lisi and A Marrone, *Phys. Rev. D* **89(1)**, 013001 (2014), arXiv:1309.1638 [hep-ph]

[14] M Ghosh, P Ghoshal, S Goswami and S K Raut, *Phys. Rev. D* **89**, 011301 (2014), arXiv:1306.2500 [hep-ph]

[15] M Ghosh, P Ghoshal, S Goswami and S K Raut, *Nucl. Phys. B* **884**, 274 (2014), arXiv:1401.7243 [hep-ph]