Evidence for leptonic CP phase from NO$\nu$A, T2K and ICAL

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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 ($\theta_{12}, \theta_{23}$ and $\theta_{13}$) and one phase ($\delta_{\text{CP}}$) known as the leptonic CP phase. Neutrino oscillation also involves two mass squared differences: the solar mass square difference ($\Delta m^2_{12} = m^2_2 - m^2_1$) and the atmospheric mass square difference ($\Delta m^2_{31} = |m^2_3 - m^2_1|$). 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 $\theta_{23}$, i.e., lower ($\theta_{23} < 45^\circ$: LO) or higher ($\theta_{23} > 45^\circ$: 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 NO$\nu$A, 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 NO$\nu$A/T2K is poorer for some parameter ranges. Addition of ICAL data to T2K and NO$\nu$A can exclude these spurious wrong-hierarchy and/or wrong-octant solutions and cause a significant increase in the range of $\delta_{\text{CP}}$ values for which a hint of CP violation can be achieved. Similarly, the precision with which $\delta_{\text{CP}}$ can be measured also improves with the inclusion of ICAL data.

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

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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 $\delta_{\text{CP}}$ 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 NO$\nu$A 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 $\delta_{\text{CP}}$ [4]. Hence, a combination of long-baseline (LBL) and atmospheric data can substantially improve the ability of the LBL experiments to measure $\delta_{\text{CP}}$. In this work, we demonstrate that the CP sensitivity of T2K and NO$\nu$A 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]

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

where $\Delta = \Delta_{31}L/4E$, $s_{ij}(c_{ij}) \equiv \sin \theta_{ij}(\cos \theta_{ij})$, $\hat{A} = 2\sqrt{2}G_F n_e E/\Delta_{31}$, $G_F$ is the Fermi constant and $n_e$ is the electron number density. For neutrinos, the signs of $A$ and $\Delta$ 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-$\delta_{\text{CP}}$ degeneracy [7].

3. Experimental specification

For the long-baseline experiments NO$\nu$A 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 NO$\nu$A ($L = 812$ 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].

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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 NO\(\nu\)A, T2K and ICAL

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

\[ \chi^2 = \min \frac{(N_{\text{ex}}(\delta_{\text{CP}}) - N_{\text{th}}(\delta_{\text{CP}}^{\text{test}} = 0, 180^\circ))^2}{N_{\text{ex}}(\delta_{\text{CP}})} \],

where \( N_{\text{ex}} \) and \( N_{\text{th}} \) are the true and test events respectively.

From the upper panels of figure 1, it may be observed that the CPV discovery of NO\(\nu\)A+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 \( \chi^2 \) minimum for CPV discovery occurs in the wrong hierarchy. For atmospheric neutrinos, the baselines are related to the zenith angle \( \theta_{23} \). As \( \delta_{\text{CP}} \) always

![Figure 1. CPV discovery vs. true \( \delta_{\text{CP}} \) for NO\(\nu\)A+T2K (upper row) and NO\(\nu\)A+T2K+ICAL (lower row), for three values of \( \theta_{23} \), \( \sin^2 2\theta_{13} = 0.1 \) and a true normal (left panels) or inverted (right panels) mass hierarchy, with 500 kt yr exposure for ICAL.](image)
appears along with a factor of $\cos \Delta$ or $\sin \Delta$, even for a 10% error range in $\theta_z$, this oscillating term varies over an entire cycle. As a result, the $\delta_{CP}$-sensitivity gets washed out. Thus, atmospheric neutrino experiments by themselves are not sensitive to $\delta_{CP}$, 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 NO,$\nu$A+T2K, the drop in the CPV discovery is resolved. The results depend significantly on the true value of $\theta_{23}$. As $\theta_{23}$ increases, hierarchy sensitivity increases but CP sensitivity decreases. As a result, for $\theta_{23} = 51^\circ$, the $\chi^2$ minima for NO,$\nu$A+T2K comes in the correct hierarchy and the ICAL information becomes superfluous.

5. CP precision of NO,$\nu$A, T2K and ICAL

The precision $\chi^2$ is defined as

$$\chi^2 = \min \left( \frac{(N_{ex}(\delta_{CP}^{fr}) - N_{th}(\delta_{CP}^{test}))^2}{N_{ex}(\delta_{CP}^{fr})} \right).$$

Figure 2. CP precision at 90%/95% CL for NO,$\nu$A+T2K (upper row) and NO,$\nu$A+T2K+ICAL (lower row), for $\theta_{23} = 39^\circ$, $\sin^2 2\theta_{13} = 0.1$ and a true normal (left panels) or inverted (right panels) mass hierarchy, with 250 kt yr exposure for ICAL.
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In figure 2, we plot the CP precision in $\delta_{CP}(true)$ vs. $\delta_{CP}(test)$ plane for NO\text{\textit{v}}A, 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 $90^{\circ} - \theta_{\mu\mu}$ in the disappearance channel.

The allowed values of $\delta_{CP}$ 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-$\delta_{CP}$ degeneracy, we see that for NO\text{\textit{v}}A+T2K, other $\delta_{CP}$ 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 $2\sigma$ 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. $\theta_{13}$ and $\theta_{23}$ dependence in CPV discovery $\chi^{2}$

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, $\theta_{13}$ and $\theta_{23}$ are expected to have similar dependence on $\delta_{CP}$.

For illustrative purposes, the CP $\chi^{2}$ can be written as

$$\chi^{2} \sim \frac{P(\delta_{CP}) \sin^{2} 2\theta_{13}}{Q \sin^{2} \theta_{13} + R(\delta_{CP}) \sin 2\theta_{13}},$$

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

These features are clearly reflected in figure 3. The left panel shows that sensitivity to CP violation is maximum for NO\text{\textit{v}}A+T2K in the current $3\sigma$ range of $\theta_{13}$ (region between the vertical black lines). From the right panel, we find that for $40^{\circ} < \theta_{\mu\mu}^{Tr} < 49^{\circ}$, there is a wiggle signalling the octant-$\delta_{CP}$ degeneracy. The behaviour is different for $\delta_{CP}^{Tr} = \pm 90^{\circ}$ depending on the true octant.

![Figure 3](image-url)  

**Figure 3.** CP violation discovery potential of NO\text{\textit{v}}A+T2K as a function of true $\theta_{13}$. NH is fixed.
This is illustrated in figure 4, where we can notice a drop at $-90^\circ$ for $\theta_{\mu\mu} = 43^\circ$ and at $+90^\circ$ for $\theta_{\mu\mu} = 49^\circ$ for NO$\nu$A+T2K, when the octant is assumed to be unknown. But when ICAL is added, it restricts the $\delta_{CP}$-octant degeneracy to $41^\circ < \theta_{\mu\mu} < 48^\circ$. Thus, we can see a partial improvement at $\theta_{\mu\mu} = 43^\circ$ but the degeneracy is fully resolved at $\theta_{\mu\mu} = 49^\circ$ 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 NO$\nu$A and the atmospheric neutrino experiment ICAL@INO. We see that due to hierarchy-$\delta_{CP}$ degeneracy, there is a drop in CP sensitivity for NO$\nu$A 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/NO$\nu$A. We have also shown that the current values of $\theta_{13}$ lies in a region where CP sensitivity is maximum. There is also a degeneracy of $\delta_{CP}$ with the octant in the range $40^\circ < \theta_{\mu\mu} < 49^\circ$ for T2K+NO$\nu$A. Addition of ICAL data helps to restrict the degeneracy at $41^\circ < \theta_{\mu\mu} < 48^\circ$. 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 NO$\nu$A.

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

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