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Resolving the octant of θ_{23} with T2K and NOνA

Sanjib Kumar Agarwalla
Institute of Physics, Sachivalaya Marg, Sainik School Post, Bhubaneswar 751005, India
E-mail: sanjib@iopb.res.in

Suprabh Prakash*
Harish-Chandra Research Institute, Chhatnag Road, Jhunsi, Allahabad 221019, Allahabad, India
E-mail: suprabhprakash@hri.res.in

S. Uma Sankar
Department of Physics, Indian Institute of Technology Bombay, Mumbai 400076, India
E-mail: uma@phy.iitb.ac.in

Preliminary results of MINOS experiment indicate that θ_{23} is not maximal. Global fits to world neutrino data suggest two nearly degenerate solutions for θ_{23}: one in the lower octant (LO: $\theta_{23} < 45^\circ$) and the other in the higher octant (HO: $\theta_{23} > 45^\circ$). $\nu_\mu \to \nu_e$ oscillations in superbeam experiments are sensitive to the octant and are capable of resolving this degeneracy. We study the prospects of this resolution by the current T2K and upcoming NOνA experiments. Because of the hierarchy-$\delta_{\rm CP}$ degeneracy and the octant-$\delta_{\rm CP}$ degeneracy, the impact of hierarchy on octant resolution has to be taken into account. As in the case of hierarchy determination, there exist favorable (unfavorable) values of $\delta_{\rm CP}$ for which octant resolution is easy (challenging). However, for octant resolution the unfavorable $\delta_{\rm CP}$ values of the neutrino data are favorable for the anti-neutrino data and vice-verse. This is in contrast to the case of hierarchy determination. In this work, we compute the combined sensitivity of T2K and NOνA to resolve the octant ambiguity. If $\sin^2\theta_{23} = 0.41$, then NOνA can rule out all the values of θ_{23} in HO at 2σ C.L., irrespective of the hierarchy and $\delta_{\rm CP}$. We show that a balanced neutrino-anti-neutrino run of T2K is better for octant resolution compared to pure neutrino run.

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*Speaker.

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1. Introduction

Our present knowledge of θ_{23} comes from two sources: a) atmospheric neutrinos and b) accelerator neutrinos. In both cases, the muon neutrino disappearance is parametrized in the form of two-flavor survival probability

$$P_{\mu\mu} = 1 - \sin^2 2\theta_{\text{eff}} \sin^2\left(\frac{\Delta m^2_{\text{eff}} L}{4E}\right). \tag{1.1}$$

Global fits, using three-flavor oscillations, give information directly on θ_{23} rather than θ_{eff} [1, 2, 3]. A common feature that has emerged from all the three global fits of the world neutrino data is that we now have indication for non-maximal θ_{23}. Thus, we have the two degenerate solutions: either θ_{23} belongs to the LO ($\sin^2\theta_{23} \approx 0.4$) or it lies in the HO ($\sin^2\theta_{23} \approx 0.6$). This degeneracy, in principle, can be broken with the help of $\nu_\mu \leftrightarrow \nu_e$ oscillation data.

In the past, when we had only an upper bound on θ_{13}, a possible way of resolving this degeneracy by combining future reactor data with accelerator ν_μ disappearance and ν_e appearance measurements was suggested in [4]. Adding the information from the 'silver' channel ($\nu_e \to \nu_\tau$) to the 'golden' channel ($\nu_e \to \nu_\mu$) in the proposed neutrino factory setup was demonstrated in [5]. The possibility of determining the deviation of θ_{23} from maximal mixing and consequently, the correct octant of θ_{23} in very long-baseline neutrino oscillation experiments and as well as in future atmospheric neutrino experiments has been discussed previously. In this work, we study the capabilities of the present-generation long-baseline superbeam experiments T2K and NOνA towards the resolution of the octant of θ_{23}.

2. Results

We study the behavior of $\Delta\chi^2$ between the true and the wrong octants as a function of true δ_{CP}. Here, the $\Delta\chi^2$ is computed in the following way. First, we fix the true value of δ_{CP}. We take $\sin^2\theta_{23}$ to be its best-fit value in the true octant: 0.41 for LO and 0.59 for HO. If the LO (HO) is the true octant, the test values of $\sin^2\theta_{23}$ in the HO (LO) are varied within the range $[0.5, 0.67]$ ($[0.33, 0.5]$), where 0.67 (0.33) is the 3σ upper (lower) limit of the allowed range of $\sin^2\theta_{23}$. The $\Delta\chi^2$ is computed between the spectra with the best-fit $\sin^2\theta_{23}$ of the true octant and that with various test values in the wrong octant and is marginalized over other neutrino parameters, especially the hierarchy, $\sin^2 2\theta_{13}$ and δ_{CP}. Fig. 1 shows the minimum of this $\Delta\chi^2$ vs. the true value of δ_{CP}.

From Fig. 1, we see that the NOνA data by itself can almost rule out the wrong octant at 2σ, if LO is the true octant. The $\Delta\chi^2$ dips just below 4 for true $\delta_{\text{CP}} \sim 0(180^\circ)$ if the true hierarchy is NH (IH). But, as argued earlier, this small allowed region can be effectively discriminated because of the relatively large $\Delta\chi^2$. If HO is the true octant, then NOνA data is not sufficient to rule out the wrong octant as seen in top panels of Fig. 1. In fact, the wrong octant can be ruled out only for about half of the true δ_{CP} values. But, addition of T2K data improves the octant determination ability significantly.

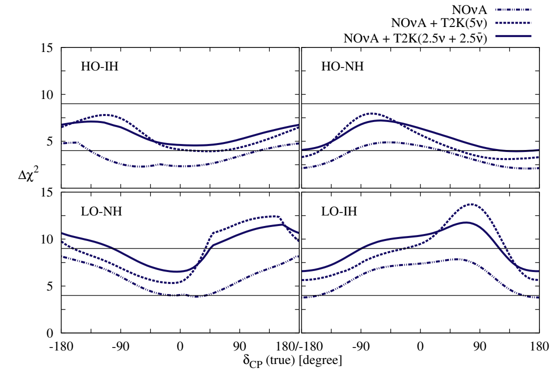

Figure 1: Octant resolving capability as a function of true $\delta_{\rm CP}$ for T2K and NOνA. The top-left (top-right) panel corresponds to HO-IH (HO-NH) being the true octant-hierarchy combination. The bottom-left (bottom-right) panel corresponds to LO-NH (LO-IH) being the true octant-hierarchy combination.

From bottom panels of Fig. 1, we see that the combined data from NOνA and T2K (5ν) give a 2σ octant resolution for all values of true $\delta_{\rm CP}$, if LO is the true octant. However, from the top panels of this figure, we see that this combined data can rule out the wrong octant at 2σ for HO-IH, but not for HO-NH. The problem of HO-NH can be solved if the T2K has equal ν and $\bar{\nu}$ runs of 2.5 years each. This change improves the octant determination for the unfavorable values of true $\delta_{\rm CP}$ (where $\Delta\chi^2$ is minimum) for all four combinations of hierarchy and octant. In particular, for the case of HO-NH, it leads to a complete ruling out of the wrong octant at 2σ for all values of true $\delta_{\rm CP}$. Thus, balanced runs of T2K in $\nu-\bar{\nu}$ mode is preferred over a pure ν run because of better octant determination capability.

Fig. 1 shows that the combined data from NOνA and T2K has a better overall octant resolving capability if LO is the true octant. We found out that this feature of LO being more favorable compared to HO is a consequence of marginalization over the oscillation parameters (mainly $\delta_{\rm CP}$) and the systematic uncertainties. We checked that in the absence of any kind of marginalization $\Delta\chi^2_{\rm HO}$ is consistently larger than $\Delta\chi^2_{\rm LO}$, as expected from the larger number of events for HO.

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