Neutrino/Anti-neutrino oscillation analysis using non-identical atmospheric oscillation parameters

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Introduction

Neutrino oscillations are well described by mass square splittings and mixing angles of Pontecorvo-Maki-Nakagawa-Sakata (PMNS) mixing matrix. Under the CPT symmetry, these oscillation parameters for neutrino and antineutrino are expected to be identical. Any difference in the measurement of neutrino and anti-neutrino oscillation parameters may indicate a hint for CPT violation or new physics. The Iron Calorimeter (ICAL) detector at the India-based Neutrino Observatory (INO) \cite{1} is a prime experiment aimed to resolve various issues in neutrino physics using atmospheric neutrino source with the earth matter effects. We present a search for difference in neutrino and anti-neutrino oscillation parameters assuming that the oscillation parameters of neutrinos governing survival probabilities ($\nu_\mu \rightarrow \nu_\mu$) are different from that describing for anti-neutrinos $P(\bar{\nu}_\mu \rightarrow \nu_\mu)$. We show the ICAL sensitivity to confirm a non-zero value of neutrinos governing survival probabilities ($\nu_\mu \rightarrow \nu_\mu$), $|\Delta m^2_{32}|$, $\sin^2 \theta_{23}$, $|\Delta m^2_{32}|$, and $\sin^2 \theta_{23}$ are non-identical. We use the same neutrino events data set, flavor oscillations, detector smearing and resolutions and the binning of events in several observed bins as explained in earlier ICAL analysis \cite{2}. The “pulled” $\chi^2$ analysis has been performed for two studies:

(1) Fixed true values:

<table>
<thead>
<tr>
<th>Osc. parameters</th>
<th>True values</th>
<th>Marginalization</th>
</tr>
</thead>
<tbody>
<tr>
<td>$</td>
<td>\Delta m^2_{32}</td>
<td>$ (eV$^2$)</td>
</tr>
<tr>
<td>$</td>
<td>\Delta m^2_{32}</td>
<td>$ (eV$^2$)</td>
</tr>
<tr>
<td>$\sin^2 \theta_{23}$</td>
<td>0.5</td>
<td>0.4-0.6</td>
</tr>
<tr>
<td>$\sin^2 \theta_{23}$</td>
<td>0.55</td>
<td>0.4-0.6</td>
</tr>
</tbody>
</table>

TABLE I: True values of the neutrino/antineutrino oscillation parameters.

Here, $\chi^2$ have been calculated as a function of four atmospheric oscillation parameters ($|\Delta m^2_{32}|$, $\sin^2 \theta_{23}$, $|\Delta m^2_{32}|$, $\sin^2 \theta_{23}$). True values of all four oscillation parameters are fixed as shown in Table I while observed four parameters ($|\Delta m^2_{32}|$, $\sin^2 \theta_{23}$, $|\Delta m^2_{32}|$, $\sin^2 \theta_{23}$) are varied simultaneously in neutrino and anti-neutrino plane within their given marginalization range. The $\chi^2$ for neutrino and anti-neutrino has been calculated separately, and a combined $\chi^2$ sensitivity is considered for parameter estimation. Fig. 1 shows the sensitive region as a function of $|\Delta m^2_{32}|$, and ($\sin^2 \theta_{23}$, $\sin^2 \theta_{23}$) parameter space at different Confidence Levels (C.L.)

(2) With variation in true values: Here, the True values of oscillation parameters have been allowed to vary independently as given in Table II. These parameters are varied simultaneously in a grid of $6 \times 5$ for neutrino plane and $6 \times 5$ for anti-neutrino plane. To test the null hypothesis mentioned in Table II, we estimate the $\chi^2(\nu + \nu)$ only for observed ($|\Delta m^2_{32}|$, $|\Delta m^2_{32}|$) and ($\sin^2 \theta_{23}$, $\sin^2 \theta_{23}$) values. The $\chi^2$ is calculated for each set of

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FIG. 1: The sensitivity region of the ICAL detector as a function of $(|\Delta m^2_{32}| - |\Delta m^2_{32}|)$ and $(\sin^2 \theta_{23} - \sin^2 \bar{\theta}_{23})$ parameter space at different Confidence Levels.

FIG. 2: The INO-ICAL sensitivity for $(|\Delta m^2_{32}| - |\Delta m^2_{32}|)_{\chi^2}$ at 1σ, 2σ and 3σ confidence levels.

True values of $|\Delta m^2_{32}|$, $\sin^2 \theta_{23}$, $|\Delta m^2_{32}|$, and $\sin^2 \bar{\theta}_{23}$.

<table>
<thead>
<tr>
<th>True oscillation parameters</th>
<th>Marginalization range</th>
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<tbody>
<tr>
<td>$</td>
<td>\Delta m^2_{32}</td>
</tr>
<tr>
<td>$</td>
<td>\Delta m^2_{32}</td>
</tr>
<tr>
<td>$\sin^2 \theta_{23}$</td>
<td>0.3-0.7</td>
</tr>
<tr>
<td>$\sin^2 \bar{\theta}_{23}$</td>
<td>0.3-0.7</td>
</tr>
</tbody>
</table>

Null hypothesis

$|\Delta m^2_{32}| = |\Delta m^2_{32}|$ (eV$^2$) $\times$ 10$^{-3}$

$\sin^2 \theta_{23} = \sin^2 \bar{\theta}_{23}$

TABLE II: The true values of neutrino and anti-neutrino oscillation parameters and their marginalization range.

A minimum $\chi^2$ has been binned as a function of differences in the true values of $|\Delta m^2_{32}| - |\Delta m^2_{32}|_{\chi^2}$ keeping marginalization over $\sin^2 \theta_{23}$ and $\sin^2 \bar{\theta}_{23}$ for each set of difference $|\Delta m^2_{32}| - |\Delta m^2_{32}|_{\chi^2}$, minimum $\Delta \chi^2 = \chi^2 - \chi^2_{\chi^2}$ has been plotted as the functions of set of differences. Fig. 2 represents the INO-ICAL potential for rulling out the null hypothesis at different confidence levels.

Results & Conclusions

Non-identical four oscillation parameters fitting technique for any difference in neutrino and anti-neutrino oscillation parameters has been performed. Allowed parameter space for any difference in the oscillation parameters as a results of given fixed true values has been shown in Fig. 1. The INO-ICAL potential for ruling out the null hypothesis $|\Delta m^2_{32}| = |\Delta m^2_{32}|$ as a results of variation in true values has been presented (Fig. 2). It has been found that if the difference of true values of $|\Delta m^2_{32}| - |\Delta m^2_{32}|_{\chi^2} \geq 0.7 \times 10^{-3}$ eV$^2$ or $|\Delta m^2_{32}| - |\Delta m^2_{32}|_{\chi^2} \leq -0.7 \times 10^{-3}$ eV$^2$, then the ICAL detector can differentiate between $\nu_\mu$ or $\bar{\nu}_\mu$ parameters at more than 3σ level.

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References


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