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Precision measurement of neutrino oscillation parameters at INO-ICAL detector

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Abstract. A magnetized Iron CALorimeter (ICAL) detector at the India-based neutrino observatory (INO) is used to study neutrino oscillation sensitivity using atmospheric muon neutrino source. The ICAL detector will be able to detect muon tracks and hadron showers produced by neutrino interactions with the iron target. We have performed precision measurement analysis for the atmospheric neutrino oscillation parameters with the muon neutrino events, generated by Monte Carlo NUANCE event generator. A marginalized χ^2 analysis based on reconstructed neutrino energy and muon zenith angle binning scheme has been performed to determine the sensitivity for the atmospheric neutrino mixing parameters, $\sin^2\theta_{23}$ and $|\Delta m^2_{23}|$.

Keywords. India-based neutrino observatory; iron calorimeter; neutrino oscillations.

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1. Introduction

Neutrino oscillation is now a well-established fact and is a direct indication for physics beyond the Standard Model. Recent discovery of the relatively large value of the third neutrino mixing angle θ_{13} from various experiments has heralded a new era in neutrino physics. But, various unsolved mysteries related to neutrinos such as, actual mass of neutrinos, measurement of Dirac δ_{CP} phase, measurement of neutrino mass hierarchy, etc. are still there. A large number of neutrino experiments are in operation or proposed, to resolve these mysteries. In the same stream, India-based neutrino observatory (INO) [1] experiment has been proposed, to be built in India with a large magnetized Iron CALorimeter (ICAL) detector. In this paper, we show the precision measurement analysis for the ICAL detector using atmospheric muon neutrino (antineutrinos) oscillation events, generated by Monte Carlo NUANCE [2] event generator. The analysis has been performed for a 10-year exposure of the ICAL detector. Various resolutions and efficiencies obtained by the INO Collaboration are implemented to reconstruct neutrino energy and muon direction. A marginalized χ^2 analysis based on neutrino energy and muon zenith angle binning scheme has been performed to determine the sensitivity for the atmospheric neutrino mixing parameters, $\sin^2\theta_{23}$ and $|\Delta m^2_{32}|$.

2. The ICAL detector

The India-based neutrino observatory (INO) has planned to set up an underground laboratory in India to study atmospheric neutrinos. INO will host a 50 kt magnetized iron calorimeter (ICAL) detector which consists of three modules, each of dimension 16 m $\times$ 16 m $\times$ 14.5 m. The detector consists of a stack of 151 horizontal layers of 5.6 cm thick iron slab interleaved within 4 cm gap for the active detector element. Glass resistive plate chambers (RPCs) of 2 m $\times$ 2 m dimension will be used as an active part of the detector. Atmospheric neutrino interaction with the iron target produces muons along with shower of hadrons through a charge–current interaction process. ICAL detector will be able to detect muons using their long tracks and hadron shower hits produced by neutrino events. ICAL will have the unique capability to detect the charge of the produced muon through its magnetic field which is around 1.5 T and hence can determine the charge of neutrinos. As neutrinos and antineutrinos interact differently with matter, the atmospheric neutrinos with large coverage of flight distance can reveal the mass hierarchy problem while passing through Earth. Thus, ICAL with atmospheric neutrino source has the potential to solve the unknown correct mass spectrum of neutrinos.

3. Analysis

3.1 *Event generation and oscillation effect*

The atmospheric neutrino events are generated with the available three-dimensional neutrino flux provided by Honda *et al* [3] using ICAL detector specifications. The atmospheric muon–neutrino (antineutrinos) interactions are simulated for 1000 yr exposure of 50 kt ICAL detector and then normalized to 10 yr exposure to keep Monte Carlo fluctuations under control. Only charge–current (CC) interactions are considered for the present analysis. At first, each event is generated in the absence of oscillations and then the effects of oscillations are included using the re-weighting algorithm similar to the method described in the earlier ICAL analyses [4,5]. The current best-fit values and errors in the oscillation parameters used for analysis are shown in table 1. For each neutrino event of

Table 1. Oscillation parameters used for the analysis.

Oscillation parameters	True values	Marginalization range
$\sin^2(2\theta_{12})$	0.86	Fixed
$\sin^2(\theta_{23})$	0.5	0.4–0.6 (3σ range)
$\sin^2(\theta_{13})$	0.03	0.02–0.04 (3σ range)
Δm^2_{21} (eV^2)	7.6×10^{-5}	Fixed
Δm^2_{32} (eV^2)	2.4×10^{-3}	(2.1–2.6) $\times10^{-3}$ (3σ range)
δ_{CP}	0.0	Fixed

a given energy E_ν and zenith direction θ_z, oscillation probabilities are estimated in the framework of three-flavour mixing taking matter effects into account.

3.2 *ICAL detector resolutions and the neutrino energy reconstruction*

Reconstruction of the neutrino energy requires the measurement of muon as well as hadron energy. Once we have the reconstructed muon and hadron energies, we directly add them together to get the final reconstructed neutrino energy. Muon and hadron energy resolutions have been obtained by the INO Collaboration as a function of true energy E_{true} and direction $\cos\theta_{\text{true}}$ of the particle using a GEANT4-based code. Muons give clear track of hits inside the magnetized detector. Therefore, the energy of muons can be reconstructed easily using a track fitting algorithm. It was observed that the energy of muons reconstructed by ICAL detector follows Gaussian distribution for $E_\mu \geq 1$ GeV, whereas it follows Landau distribution function for $E_\mu < 1$ GeV [6]. Hadrons deposited their energies in a shower-like pattern. The total energy deposited by the hadron shower ($E'_{\text{had}} = E_\nu - E_\mu$) has been used to calibrate the detector response. It has been found that hadron hit patterns follow Vavilov distribution and the hadron energy resolution is then shown as a function of E'_{had}. The details of INO resolution analysis can be found in [7,8]. In the present analysis, muon energy and angular resolutions are implemented by smearing true muon energy and direction of each μ^+ and μ^- event using the ICAL muon resolution functions. Energies of hadron events are smeared using ICAL hadron resolution functions. Reconstructed neutrino energy is then taken as the sum of reconstructed muon and hadron energy. We have also taken care of the muon's reconstruction and charge identification efficiencies provided by INO Collaboration in the present work.

3.3 χ^2 *analysis*

The oscillation parameters determining the atmospheric neutrinos are extracted by χ^2 analysis. The re-weighted events with detector resolutions and efficiencies folded in, are binned into reconstructed neutrino energy and muon direction for the estimation of χ^2. The data have been divided into ten equal neutrino energy bins in the range of 0.8–10.8 GeV with 1 GeV bin width. Twenty $\cos\theta_\mu$ direction bins in the range of -1 to 1, with equal bin width have been chosen. The above-mentioned binning scheme is applied for both ν_μ and $\bar{\nu}_\mu$ events. Here, we use the concept of maximal mixing i.e., $\sin^2\theta_{23} = 0.5$. The atmospheric mass square splittings are related to other oscillation parameters. So, for precision study we have defined it as Δm^2_{eff}, which can be written as follows:

$$\Delta m^2_{\text{eff}} = \Delta m^2_{32} - (\cos^2\theta_{12} - \cos\delta_{\text{CP}} \sin\theta_{32} \sin 2\theta_{12} \tan\theta_{23})\Delta m^2_{21}. \tag{1}$$

The other oscillation parameters (θ_{12}, Δm^2_{21} and δ_{CP}) are kept fixed for both the observed and predicted events as the marginalization over these parameters has negligible effects on the analysis results. In the present analysis, we have implemented five systematic uncertainties, 20% error on atmospheric neutrino flux normalization; 10% error on neutrino cross-section; an overall 5% statistical error; a 5% uncertainty due to zenith angle dependence of the fluxes and an energy-dependent tilt error as applied in earlier ICAL analyses [4,5]. All these systematic uncertainties are applied using the method of 'pulls' as outlined in ref. [9]. In the analysis framework, due to the fine binning, some bins have very small number of entries. Therefore, we have used the Poissonian definition of χ^2 given as

$$\chi^2(\nu_\mu) = \min \sum_{i,j} \left(2(N_{ij}^{\text{th}'}(\nu_\mu) - N_{i,j}^{\text{ex}}(\nu_\mu)) + 2N_{i,j}^{\text{ex}}(\nu_\mu) \left(\ln \frac{N_{i,j}^{\text{ex}}(\nu_\mu)}{N_{i,j}^{\text{th}'}(\nu_\mu)} \right) \right) + \sum_k \zeta_k^2, \tag{2}$$

where

$$N_{ij}^{\text{th}'}(\nu_\mu) = N_{i,j}^{\text{th}}(\nu_\mu) \left(1 + \sum_k \pi_{ij}^k \zeta_k \right). \tag{3}$$

In eq. (2), N_{ij}^{ex} are the observed number of reconstructed μ^- events generated using true values of oscillation parameters listed in table 1 in i^{th} neutrino energy bin and $j^{\text{th}} \cos\theta_\mu$ bin. In eq. (3), N_{ij}^{th} are the number of theoretically predicted events generated by varying oscillation parameters, $N_{ij}^{\text{th}'}$ shows the modified events spectrum due to different systematic uncertainties, π_{ij}^k is the systematic shift in the events of i^{th} neutrino energy bin and $j^{\text{th}} \cos\theta_\mu$ bin due to k^{th} systematic error. ζ_k is the univariate pull variable corresponding to the π_{ij}^k uncertainty. Similar expression for $\chi^2(\bar{\nu}_\mu)$ can be obtained using the reconstructed μ^+ event samples. We have calculated $\chi^2(\nu_\mu)$ and $\chi^2(\bar{\nu}_\mu)$ separately and then these two are added to get total χ^2_{total} as

$$\chi^2_{\text{total}} = \chi^2(\nu_\mu) + \chi^2(\bar{\nu}_\mu). \tag{4}$$

As the value of θ_{13} is now known to several Gaussian standard deviations (σ), we use a 10% deviation from the true value of $\sin^2\theta_{13}$ as a prior to marginalize over $\sin^2\theta_{13}$ as

$$\chi^2_{\text{ino}} = \chi^2_{\text{total}} + \left(\frac{\sin^2\theta_{13}(\text{true}) - \sin^2\theta_{13}}{\sigma_{\sin^2\theta_{13}}} \right)^2. \tag{5}$$

Finally, we minimize the χ^2_{ino} function by varying oscillation parameters within their allowed ranges over all systematic uncertainties.

4. Results

We have derived the measurement contours of the atmospheric oscillation parameters in 3-flavour mixing using Earth matter effect. The two-dimensional confidence region of the oscillation parameters ($|\Delta m^2_{\text{eff}}|$, $\sin^2\theta_{23}$) is determined from $\Delta\chi^2_{\text{total}}$ around the best fit. The resultant region is shown in figure 1. We have obtained these contour plots by assuming $\Delta\chi^2_{\text{total}} = \chi^2_{\text{min}} + m$, where χ^2_{min} is the minimum value of χ^2_{total} for each set of oscillation parameters and values of m are taken as 2.30, 4.61 and 9.21 corresponding to 68, 90 and 99% confidence levels respectively. Figure 2 depicts the one-dimensional plot for the measurement of test parameter $\sin^2\theta_{23}$ (figure 2b) at fixed $|\Delta m^2_{\text{eff}}| = 2.4 \times 10^{-3}$ (eV^2) and for $|\Delta m^2_{\text{eff}}|$ at fixed $\sin^2\theta_{23} = 0.5$ (figure 2a).

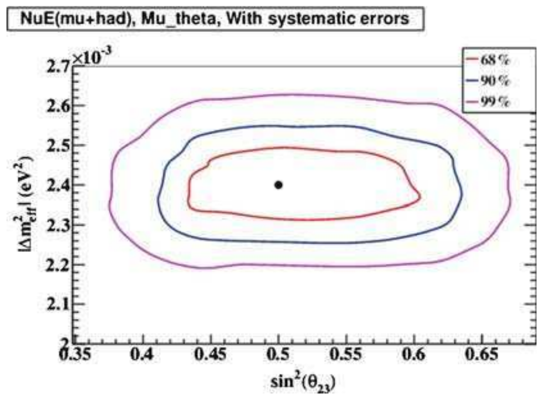

Figure 1. Contour plot for 68, 90 and 99% confidence level for 10-year exposure of the ICAL detector.

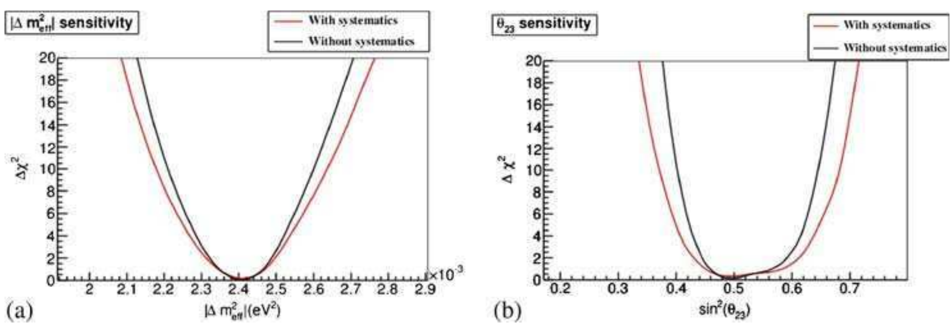

Figure 2. $\Delta\chi^2$ as a function of test values of $|\Delta m^2_{\rm eff}|$ (**a**) and $\Delta\chi^2$ as a function of test values of $\sin^2\theta_{23}$ (**b**).

The precision on the oscillation parameters can be defined as

$$\text{Precision} = \frac{P_{\max} - P_{\min}}{P_{\max} + P_{\min}}, \tag{6}$$

where $P_{\max}$ and $P_{\min}$ are the maximum and minimum values of the concerned oscillation parameters at the given confidence level. The current study shows that ICAL is capable of measuring the atmospheric mixing angle $\sin^2\theta_{23}$ with a precision of 16, 21 and 28% at 68, 90 and 99% confidence levels respectively. The atmospheric mass square splitting $|\Delta m^2_{\rm eff}|$ can be measured with a precision of 3.75, 6 and 9% at 68, 90 and 99% confidence levels respectively.

5. Conclusions

We have studied the capability of the ICAL detector for the precise measurement of atmospheric neutrino oscillation parameters using neutrino energy and muon angle observables. A Monte Carlo simulation using NUANCE-generated neutrino data for 10-year exposure of ICAL detector has been carried out. Finally, a marginalized χ^2 analysis was carried out in bins of neutrino energy and muon angle using realistic detector resolutions for measuring $\sin^2\theta_{23}$ and $|\Delta m^2_{\rm eff}|$. On comparing these results with the results shown in [4], we find that there is an improvement of 6% and 16% on the precision measurement of $\sin^2\theta_{23}$ and $|\Delta m^2_{\rm eff}|$ parameters respectively using neutrino energy and muon angle observables over muon energy and muon angle analysis [4]. Results presented here can be further improved using improved resolutions of ICAL and with fine energy and direction binning. Moreover, this study shows that the ICAL experiment has the capability of using hadron information to further improve the measurement of oscillation parameters.

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References

[1] The Technical Design Report of INO-ICAL Detector
[2] D Casper, *Nucl. Phys. Proc. Suppl.* **112**, 161 (2002), arXiv:0208030 [hep-ph]
[3] M Honda *et al*, *Phys. Rev. D* **70** (2004), arXiv:0404457 [astro-ph]
[4] T Thakore *et al*, *J. High Energy Phys.* **05**, 058 (2013)
[5] Anushree Ghosh *et al*, *J. High Energy Phys.* **04**, 009 (2013)
[6] GEANT simulation toolkit wwwasd.web.cern.ch/wwwasd/geant/
[7] Animesh Chatterjee *et al*, arXiv:1405.7243[physics.ins-det] (2014)
[8] M M Devi *et al*, *J. Instrum.* **8**, P11003 (2013)
[9] Maltoni *et al*, arXiv:0404085v1 [hep-ph]