

Precision measurement of neutrino oscillation parameters @ INO-ICAL detector

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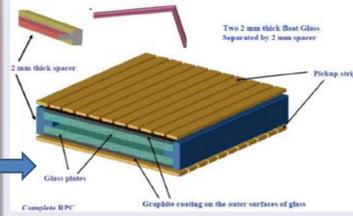


Introduction

India-based Neutrino Observatory (INO) is a mega science project to study the properties of atmospheric neutrinos and anti-neutrinos with a large magnetised Iron CALorimeter (ICAL) detector. Precision measurement of oscillation parameters and determination of neutrino mass hierarchy are the primary goals of INO. Here, we present INO-ICAL capability for measuring the atmospheric neutrino oscillation parameters $|\Delta m^2_{\text{atm}}|$ and $\sin^2\theta_{23}$.

ICAL SPECIFICATIONS

- ❖ Total no. of modules : 3
- ❖ Dimension : 16m x 16m x 14.5m (for one module)
- ❖ Absorber material : Iron (5.6 cm. thick plates)
- ❖ Active Detector : Resistive Plate Chambers of 2m x 2m dimensions
- ❖ Total No. of Layers : 150
- ❖ Magnetic field : ~1.5 Tesla
- ❖ Total Mass : 50 ktons
- ❖ Location : Theni District, Tamilnadu, India



- Gaseous detector
- Two dimensional output
- Cheap and Best
- Efficiency > 95% at high voltage (~10kV)
- Good spatial (~3 cm) and time resolution (~1ns)

Fig 2: Resistive Plate Chamber and its specifications

- ❑ ICAL detector is sensitive for atmospheric ν_μ and anti- ν_μ
- ❑ Neutrino interactions with the detector produce charged muons and hadrons
- ❑ Magnetised ICAL can easily identify the μ^+ & μ^- events from their curvatures and track bending
- ❑ Muons can be identified & reconstructed using their tracks in magnetised detector and hadrons can be calibrated with their shower hits in the detector
- ❑ Neutrino energy and angle can be reconstructed using the information from muons and hadrons

Fig 1: Schematic view of ICAL detector

Analysis Procedure

Reconstructed neutrino energy and muon direction based binned χ^2 analysis have been performed using realistic INO detector resolutions & efficiencies. The methodology of the analysis is as follows:

Event Generation

- ❖ Event generator used : NUANCE
- ❖ Flux: HONDA 3D flux for 50 ktons ICAL detector
- ❖ Unoscillated neutrino/anti-neutrino events are generated for 1000 years exposure of ICAL detector
- ❖ Data has been scaled down for 10 years of running ICAL for parameters estimation

Event Selection

- ❖ Charge-Current events are considered for the analysis
- ❖ A Monte Carlo acceptance/rejection method is used to introduce the oscillation effects to generated unoscillated events
- ❖ Events are selected on the basis of three flavor transition probabilities assuming Normal Hierarchy
- ❖ PREM earth density profile is used for matter effects

Detector Resolutions & Efficiencies

- ❖ Muon and hadron resolutions and efficiencies obtained by INO collaboration has been used (as shown in Fig. 4,5& 6)
- ❖ Reconstructed neutrino energy is taken as sum of reconstructed muon and hadron energy
- ❖ Reconstructed neutrino energy and muon directions are considered as observables for analysis
- ❖ Analysis has been performed separately for neutrino and anti-neutrino events

Energy & Direction Binning

- ❖ Selected data is then distributed in to 20 varied energy bins. From 0.8-5.8 GeV, 15 bins, with bin size of 0.33 GeV & from 5.8-10.8, 5 bins, with bin size of 1GeV and 20 equal $\cos\theta$ bins (ranges from -1 to 1)
- ❖ Same binning scheme is applied for neutrino and anti-neutrino events

χ^2 Analysis

- ❖ A marginalised χ^2 analysis is performed using above mentioned systematic uncertainties
- ❖ $\chi^2_{\text{total}} = \chi^2_{\text{neutrino}} + \chi^2_{\text{anti-neutrino}}$
- ❖ Poisson χ^2_{total} function is minimised using method of "Pulls" for systematics implementations
- ❖ A prior on θ_{13} has been implemented for this work

Oscillation Parameters

True values and marginalisation range of the used oscillation parameters are listed in Table 1:

Oscillation parameters	True values	Marginalisation range
$\sin^2(2\theta_{12})$	0.86	Fixed
$\sin^2(\theta_{23})$	0.5	0.4-0.6 (3 σ range)
$\sin^2(\theta_{13})$	0.03	0.02-0.04 (3 σ range)
Δm^2_{sol} (eV ²)	7.6×10^{-5}	Fixed
Δm^2_{atm} (eV ²)	2.4×10^{-3}	(2.1-2.6) $\times 10^{-3}$ (3 σ range)
δ_{cp}	0.0	Fixed

Applied Systematic Errors

- 20% flux normalisation error
- 10% cross section error
- 5% over all systematic error
- 5% energy dependent tilt error
- 5% uncertainty for zenith angle dependence of the flux

ICAL Resolutions & Efficiencies

➔ A GEANT-4 based ICAL detector simulation is used for the reconstruction of muons and hadrons

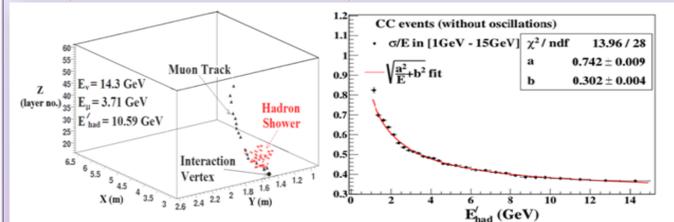


Fig 3: Neutrino interaction @ ICAL Fig 4: Hadron Energy Resolution @ ICAL
M. M. Devi et al. (2013) JINST 8 P11003

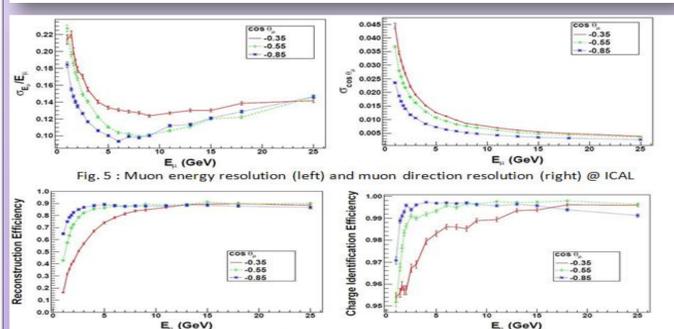


Fig 5: Muon energy resolution (left) and muon direction resolution (right) @ ICAL
Fig 6: Muon reconstruction efficiencies (left) and charge identification efficiencies (right) @ ICAL
Thakore, T. et al. (2013) JHEP05(2013) 058

Results

- ❖ We have shown the sensitivity of ICAL for atmospheric oscillation parameters as a contour plot in $|\Delta m^2_{\text{atm}}|$ and $\sin^2\theta_{23}$ parameter space (Fig. 7)

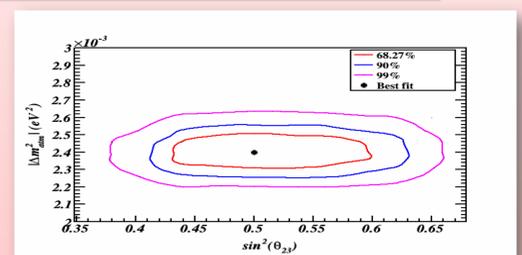


Fig 7: Contour plot for the measurement of atmospheric oscillation parameters for 10 years exposure of ICAL detector

- ❖ We have also present the one dimensional $\Delta\chi^2$ plot for the sensitivity of best fit value of each parameter by keeping other parameters fixed (Fig. 8)

- ❖ The precision on the oscillation parameters can be defined as:

$$\text{Precision} = (P_{\text{max}} - P_{\text{min}}) / (P_{\text{max}} + P_{\text{min}})$$

where P_{max} and P_{min} are the maximum and minimum values of the concerned oscillation parameters at given confidence levels

Osc. Parameters	68.27 %	90%	99%
$\sin^2\theta_{23}$	16.21%	20.90%	27.18%
$ \Delta m^2_{\text{atm}} $	4.15%	6.24%	9.0%

Table 2 shows the precision values up to which ICAL would be able to measure the $|\Delta m^2_{\text{atm}}|$ and $\sin^2\theta_{23}$ using neutrino energy and muon angle analysis procedure for 10 years of running INO-ICAL detector at different confidence levels.

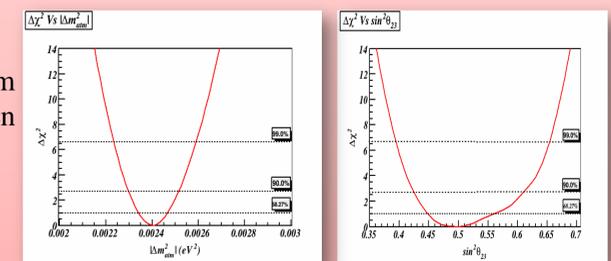


Fig 8: 1D plot for the $\Delta\chi^2$ as a function of test parameter $|\Delta m^2_{\text{atm}}|$ (left) and as a function of $\sin^2\theta_{23}$ (right) at different sigmas.

Conclusions

- ❖ Magnetised INO-ICAL detector is capable of measuring the right mass hierarchy and constrained the atmospheric neutrino oscillation parameters $|\Delta m^2_{\text{atm}}|$ and $\sin^2\theta_{23}$
- ❖ We found that ICAL is able to measure $|\Delta m^2_{\text{atm}}|$ and $\sin^2\theta_{23}$ with a precision of 9.0% and 27.18% at 3 σ level for 10 years of exposure with a given detector resolutions and efficiencies, using neutrino energy & muon angle as observables
- ❖ Present results are with the improvement of 18.62% and 5% on the precision measurement of $|\Delta m^2_{\text{atm}}|$ and $\sin^2\theta_{23}$ over the earlier ICAL analysis with muon energy & muon angle [Ref.2]

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