PROCEEDINGS OF SCIENCE

The India–based Neutrino Observatory

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The India-based Neutrino Observatory (INO) is an underground laboratory to be located in the Bodi West Hills, in the Theni district of Tamil Nadu in South India. The main experiment at INO is a magnetized iron calorimeter (ICAL) which will study the oscillations in the atmospheric neutrino sector. The ICAL will primarily aim at distinguishing the neutrino mass hierarchy through the study of the Earth's matter effects in the atmospheric ν_μ and $\bar{\nu}_\mu$. It will also determine the atmospheric neutrino mixing parameters with a fine precision and will probe the hints of new physics. The ICAL physics motivations, the detector description and present status of the detector simulation and physics reach studies are presented here.

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1. Introduction

The India-based Neutrino Observatory (INO) [1] is an underground facility to host neutrino experiments. It is to be built in the Bodi West Hills, in Theni district of Tamil Nadu in South India. The prime aim of INO is to study the neutrino oscillations with atmospheric neutrinos. Unlike the accelerator and reactor neutrino experiments where the neutrino energy (E_ν) and the baseline (L) are fixed or are within a narrow window, the atmospheric neutrinos provide a wide range of E_ν and L. The atmospheric neutrino flux is feeble, and hence the requirement of a detector with a large volume becomes essential to have significant event statistics. In order to fulfill this goal, the INO collaboration plans to build a huge magnetized Iron Calorimeter (ICAL) detector, which would be sensitive to the energy, direction and the electric charge of the final state leptons produced in charged–current (CC) interactions of the neutrinos with the target material.

The main goal of the ICAL is to study the matter effects in ν_μ and $\bar{\nu}_\mu$ separately through muon charge identification in order to determine the sign of Δm^2_{32} and hence, the neutrino mass hierarchy. The ICAL will also aim at the precise determination of the atmospheric neutrino mixing parameters $|\Delta m^2_{32}|$, θ_{23} and its octant. Apart from these, ICAL will also search for the hint of new physics, such as the CPT violation in the leptonic sector, the existence of sterile neutrinos, the signature of non standard interactions (NSI) in neutrino oscillations as well as indirect searches for dark matter.

2. The ICAL detector at INO

The ICAL will mainly look for the ν_μ and $\bar{\nu}_\mu$ induced CC interactions using magnetized iron as the target mass and the Resistive Plate Chambers (RPC) [2] as the active detector elements. It will consist of three identical and adjacent modules, each of dimension 16 m $\times$16 m $\times$14.5 m. Each of the modules will contain 151 horizontal layers of 5.6 cm thick iron plates interspersed with 4 cm gaps into which the RPC assemblies will be placed. The total mass of the ICAL will be about 50 kt.

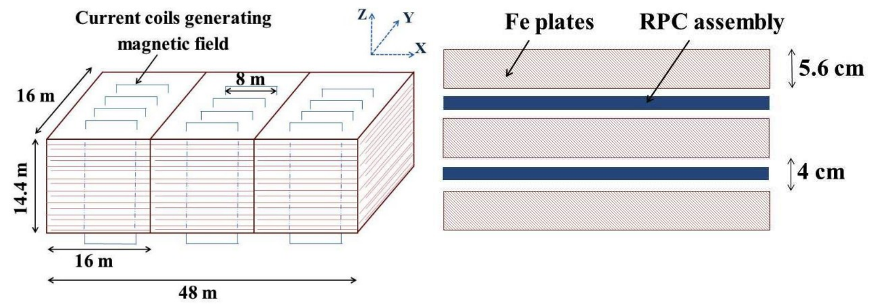

Figure 1: (Left) The schematic representation of the ICAL detector. All the three modules are shown here. The blue lines represent the current coils which magnetize the detector. (Right) The placement of the iron plates and the RPC assembly in the ICAL. Each of the three modules of the ICAl consists of 151 such layers.

A schematic diagram of the ICAL detector is shown in Fig 1. The blue lines in the three modules, as shown in the figure, show the placement of the Copper coils through which a current will be passed to generate a non–uniform magnetic field. Four coils will be there in each module with 32 turns/coil. The ICAL will be magnetized to a non–uniform field peaking at 1.4 T, to distinguish

No of modules	3
Modular dimension	16 m $\times$ 16 m $\times$ 14.4 m
Total dimension	48 m $\times$ 16 m $\times$ 14.4 m
Number of layers	151
Iron plate thickness	5.6 cm
Gap for RPC assembly	4 cm
Magnetic field	1.4 T
RPC unit dimension	195 cm $\times$ 184 cm $\times$ 2.4 cm
Readout strip width	2.8 cm
Number of RPCs/Road/Layer	8
Number of Roads/Layer/Module	8
Number of RPC units/Layer	192
Total RPC units	28,800
Number of electronic channels	3.7×10^6

Table 1: The specifications of the ICAL Detector.

between the muon and the antimuons produced in the ν_μ and $\bar{\nu}_\mu$ interactions respectively. The ICAL will have about 3.7 million readout channels. The important detector specifications have been highlighted in Table 1. A 3–level trigger scheme has been developed for event–recording in ICAL [3] .

The RPCs are gaseous parallel plate detectors, made of highly resistive electrodes such as glass or Bakelite, to track charged particles [4]. The main features of the RPCs are excellent detection efficiency, good spatial as well as position resolutions, wide area coverage and low production cost. When the gas mixture is ionized by the passage of a charged particle, the avalanches of electrons originate a discharge. The highly resistive electrodes prevent the discharge from spreading through the whole gas volume, and the electric field drops down in a small area around the point where the discharge initiates. The propagation of the electron avalanche induces a current on external electrodes. This is collected by external copper pickup strips of width 2.8 cm. The pickup strip on the two electrodes are mounted orthogonal to each other, which enables the detection of the location of the passage of the particle in pixels of area 2.8 cm $\times$2.8 cm. We term the measured location of a charged particle in the RPCs as a *hit*.

The ICAL detector would be optimized to be primarily sensitive to the atmospheric muon neutrinos in the energy range 1 – 10 GeV. The modular structure of the detector, with the horizontal layers of the iron plates and the RPC detectors allow it to have a large coverage to the direction of the incoming neutrinos, except the near horizontal ones. While the atmospheric neutrino flux provides a wide spectrum in the neutrino energy (E_ν), the detector structure enables it to be sensitive to a broad range of the path length (L) for the neutrinos penetrating through the Earth. This would be very useful to study neutrino oscillations, as the oscillation probability strongly depends on the path length L.

In addition, ICAL, being a magnetized detector, would be able to differentiate between muons and antimuons, which makes it capable of separating events induced by ν_μ and $\bar{\nu}_\mu$. Since the neutrinos and the antineutrinos experience different matter effects while propagating through the Earth, the ability to discriminate between neutrinos and antineutrinos makes the detector sensitive to the neutrino mass hierarchy, which is the main goal of the ICAL experiment. The presence of the magnetic field also improves the momentum resolution of the muons by measuring the extent of bending of the muon track in the local magnetic field.

3. The ICAL detector simulation and its response to muons and hadrons

The atmospheric ν_μ and $\bar{\nu}_\mu$ interact with the iron target mass through the three main processes: quasi–elastic (QE), resonance scattering (RS) and deep inelastic scattering (DIS). A muon is produced in the final state in case of the CC interactions. The QE process dominates in the sub–GeV neutrino energy range, with no hadrons in the final state and the muon carrying most of the available energy. The RS and DIS processes start dominating as the energy increases, and at a few GeVs DIS becomes the most prominent process. A typical RS event contain a single pion in the final state, though in a small number of events there are multiple pions. The DIS events have multiple hadrons in the final state.

A detector simulation framework to calibrate the ICAL response to the muon and hadrons has been developed using the GEANT4 simulation package [5, 6]. This framework is shown schematically in Fig. 2. The RPCs provide the (X, Y) coordinates of the hits, while the layer number gives the Z–coordinate. The hits by a muon form a track–like feature, while the hadron hits produce a shower.

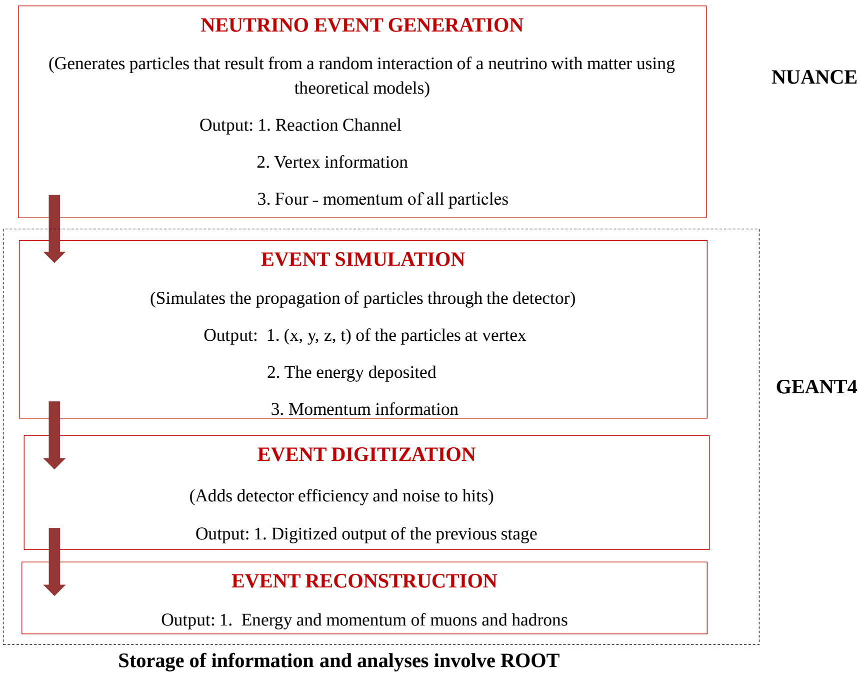

Figure 2: The framework for ICAL detector simulation.

The muon momentum reconstruction in ICAL has been done through a Kalman–filter based track finding and fitting algorithm [5, 7]. The ICAL detector is optimized for the detection of muons propagating in the detector, identification of their charges, and for accurate determination of their energies and directions. The reconstruction efficiency for muons with energies above 2 GeV is about 80%, while the charge identification efficiency of these reconstructed muons is more than 95%. The direction of these muons at the interaction vertex can be determined to the accuracy of about 1°. The muon momentum resolution is typically between (25% – 12%) in the momentum range 1 – 20 GeV, as can be seen in the left panel of Fig. 3.

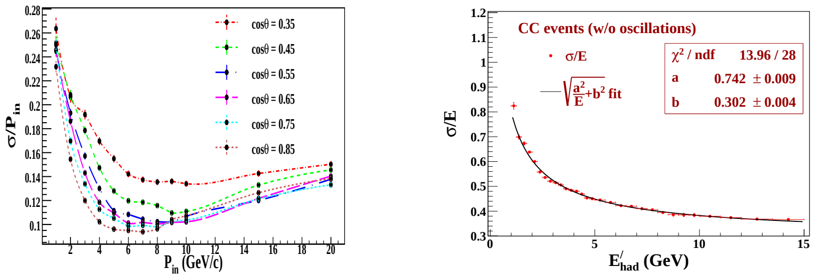

Figure 3: (Left) The muon momentum resolution as a function of the input momentum for different $\cos\theta_\mu$ [5]. (Right) The hadron energy resolution as a function of the hadron energy parametrized by E'_{had} [6].

The hadrons produce a shower of hits within a close proximity of the interaction vertex [6]. The hadron energy, parametrized by $E'_{\text{had}} \equiv E_\nu - E_\mu$, is estimated from the hadron hit multiplicity which follows the Vavilov PDF. A calibration of E'_{had} for the number of hadron hits in an event has been obtained. The hadron energy resolution of ICAL is in the range (80% – 35%) for E'_{had} between 1 – 15 GeV. The calibration of the hadron energy from the hadron hits, in terms of the Vavilov fit parameters, may further be used to reconstruct the hadron energy for the ICAL physics potential analysis. The E'_{had} resolution as a function of the E'_{had} is shown in the right panel of Fig. 3.

4. The physics potential of ICAL

The results of the physics potential studies in ICAL are summarized here.

4.1 The mass hierarchy sensitivity

In order to quantify the sensitivity of ICAL to determine the neutrino mass hierarchy, a certain hierarchy, normal or inverted, is chosen as the true hierarchy. The CC ν_μ and $\bar{\nu}_\mu$ events, generated using NUANCEv3 generator, are binned in the parameters chosen for the analysis. A χ^2 analysis is then performed, taking the systematic errors into account and marginalizing over the 3σ ranges of relevant parameters. The significance with which the wrong hierarchy can be discarded, is given by the $\Delta\chi^2_{\text{ICAL-MH}}$, which is equal to $\chi^2_{\text{ICAL}}(\text{false MH}) - \chi^2_{\text{ICAL}}(\text{true MH})$.

The analysis for mass hierarchy identification using only the muon energy and direction [8] gives a $\Delta\chi^2_{\text{ICAL-MH}} \equiv 6.5$ for 10 years of exposure of the 50 kt ICAL. A significant improvement (about 40%) in $\Delta\chi^2_{\text{ICAL-MH}}$ is obtained by including the hadron energy information in each event to the muon information [9]. In this approach, the binning is performed in the 3-dimensional parameter space (E_μ, $\cos\theta_\mu$, E'_{had}) so that the correlation between the muon and hadrons in each event is retained. The wrong mass hierarchy can be discarded with a significance ($\Delta\chi^2_{\text{ICAL-MH}}$)

of about 9.5. The comparison of the $\Delta\chi^2_{\rm ICAL-MH}$ from the 3–dimensional analysis to the muon–only analysis is shown in Fig. 4. The significance depends on the true values of θ_{23} and θ_{13}, and increases with an increase in their values. Depending on the values of these mixing angles, the significance may be in the range $\Delta\chi^2_{\rm ICAL-MH} = 7-12$ with an exposure of 500 kt–yr.

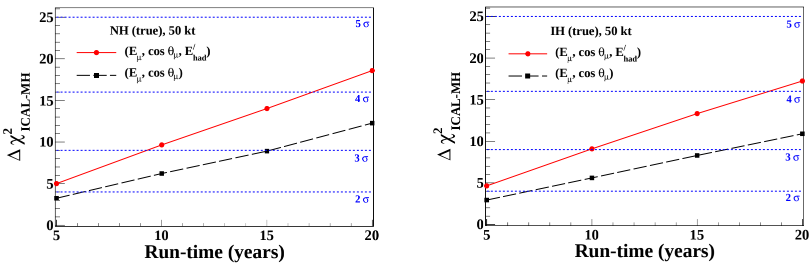

Figure 4: The $\Delta\chi^2_{\rm ICAL-MH}$ as a function of the run–time for NH (left) and IH (right) as true hierarchy. The red line shows the results with hadron information, while the black one shows those with muons only. [9]

4.2 Precision measurements of $|\Delta m^2_{32}|$ and $\sin^2\theta_{23}$

The precision in the measurements of the parameter λ ($\lambda = \sin^2\theta_{23}$ or $|\Delta m^2_{32}|$), is quantified as $\Delta\chi^2_{\rm ICAL-PM}(\lambda) = \chi^2_{\rm ICAL-PM}(\lambda) - \chi^2_0$, where χ^2_0 is the minimum value of $\chi^2_{\rm ICAL-PM}$ in the allowed parameter range. It is found that with the inclusion of $E^{'}_{\rm had}$ information, 500 kt–year of ICAL exposure will measure $\sin^2\theta_{23}$ to a relative 1σ precision of 12% and $|\Delta m^2_{32}|$ to 2.9% [9]. With the muon–only analysis, the same relative precisions would be 13.7% and 5.4%, respectively [10]. The projected reach of ICAL for a 500 kt–year exposure has been compared to the current results from other experiments in the right panel of Fig. 5. Due to the better energy measurement capabilities of ICAL, it is expected that the $|\Delta m^2_{32}|$ precision of ICAL would be much better than the atmospheric neutrino experiments that use water Cherenkov experiments. However the beam experiments will be collecting more data by the time ICAL becomes operational, and the global role of ICAL for precision measurements of these parameters will be rather complementary.

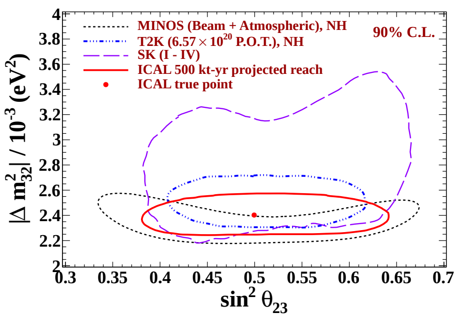

Figure 5: The ICAL 90% C.L. (2 dof) contour in the $\sin^2\theta_{23} - |\Delta m^2_{32}|$ plane. The current limits from Super-Kamiokande, MINOS, and T2K are also shown. [9]

4.3 The octant of θ_{23}

The ICAL is sensitive to the octant of θ_{23} through two effects: through the depletion in atmospheric ν_μ and $\bar{\nu}_\mu$ through the survival probability $P_{\mu\mu}$, and through the contribution of the atmospheric electron neutrinos to the observed CC muon events through the oscillation probability $P_{e\mu}$. Both of these effects are proportional to $\sin^2 2\theta_{23}$, however they act in opposite directions, thereby reducing the effective sensitivity of ICAL to the θ_{23} octant. The potential of distinguishing the octant of θ_{23} with the ICAL data alone is observed to be rather weak. A 2σ identification of the octant is possible with the 500 kt–year ICAL, only for NH as the true hierarchy and for LO as the true octant ($\sin^2\theta_{23}(\text{true}) < 0.395$) [9]. The information from other experiments would be required to be combined in order to identify the true octant.

4.4 Synergies with other experiments

4.4.1 MH sensitivity

The MH sensitivity of of the current long baseline experiments, like T2K and NOνA, depends heavily on the actual value of the CP-violating phase δ_{CP}. However, the addition of the data available from the proposed run of these experiments to that of ICAL, the mass hierarchy identification can be improved. A preliminary analysis shows that with the data from these three experiments, 3σ sensitivity may be achieved in 6 years. The large range of the baseline of the atmospheric neutrinos makes ICAL insensitive to the CP phase δ_{CP}, and its MH sensitivity is independent of the actual value of δ_{CP}. On the other hand the sensitivity of fixed-baseline experiments such as T2K and NOνA is extremely limited if $0 < \delta_{CP} < \pi$. However adding of the ICAL information ensures that the hierarchy can be identified even in these unfavoured δ_{CP} regions.

4.4.2 Determination of the CP phase

Though ICAL itself is rather insensitive to δ_{CP}, data from ICAL can still improve the determination of δ_{CP} itself [11], by providing input on mass hierarchy, as shown in Fig. 6. This is crucial particularly in the range $0 < \delta_{CP} < \pi$, precisely where the ICAL data also improved the hierarchy discrimination of NOνA and other experiments.

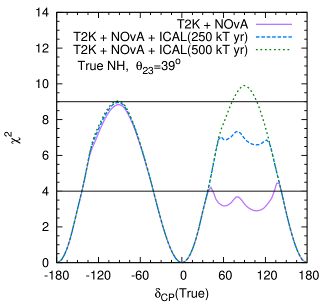

Figure 6: The CPV discovery vs true δ_{CP} for NOνA + T2K and NOνA + T2K + ICAL, for true NH. [11]

4.4.3 Other physics possibilities with ICAL

The ICAL can also be used to probe the hint of any new physics. For example, the CPT violation or Lorentz symmetry in the neutrino sector can be probed to a good precision, owing to its energy measurement capability [12]. The passage of magnetic monopoles through the detector may be probed by looking for slowly moving undeflected tracks [13]. A few studies on the ICAL scope to probe various physics aspects are now in progress.

5. Concluding remarks

The ICAL detector at INO will study the oscillations in the atmospheric neutrinos in the multi–GeV range through resonances in the earth's core. The R&D on all fronts are in progress. The capability of muon charge identification enables us to use matter effects in neutrinos and anti neutrinos separately to determine the true mass hierarchy. The ICAL, though primarily optimized for muons, will also be able to measure the hadrons and it would provide an additional boost to its physics sensitivity. The 50 kt ICAL, after 10 years of running, can discard the wrong hierarchy with median $\Delta\chi^2 \equiv 9.5$. The ICAL would also contribute to the precision measurement of the atmospheric parameters and the search for new physics.

Acknowledgments

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