The Status of INO

Sruba Goswami
Physical Research Laboratory, Navrangpura, Ahmedabad-3800058, India
E-mail: sruba@prl.res.in

Abstract. The India-based Neutrino Observatory (INO) is a proposed project to observe atmospheric neutrinos using a magnetized iron calorimeter (ICAL) detector. The unique feature of this detector is the ability to study neutrinos and antineutrinos separately owing to its charge identification capability. This makes it a very suitable detector to study the ordering of the neutrino mass states. Its other physics goals include precision measurement of atmospheric neutrino oscillation parameters, finding the octant of $\theta_{23}$ etc. In this talk I summarize the current status of the INO project and the R&D work that is underway to achieve its physics goals.

1. Introduction
Over the past few decades neutrino oscillation has emerged as an important tool for the determination of neutrino masses and mixing angles. The parameters governing oscillation are - the mass squared differences $\Delta m^2_{21} = m_2^2 - m_1^2$, $\Delta m^2_{31} = m_3^2 - m_1^2$, the mixing angles $\theta_{12}$, $\theta_{23}$, $\theta_{13}$ and the CP phase $\delta_{\text{CP}}$. Among these the unknowns are (i) neutrino mass hierarchy i.e whether the mass ordering is normal ($m_3 > m_2 > m_1$) or inverted ($m_3 < m_1 \approx m_2$), (ii) the octant of the mixing angle $\theta_{23}$ i.e whether $\theta_{23} < 45^\circ$ (lower octant) or $\theta_{23} > 45^\circ$ (higher octant) (iii) the precise value of the leptonic CP phase $\delta_{\text{CP}}$. There are many ongoing as well as planned/proposed experiments to determine these parameters. The India-based Neutrino Observatory (INO) proposal aims to address the above questions by using atmospheric neutrinos. The proposed detector is a magnetized Iron Calorimeter (ICAL) with the unique feature that it can distinguish between neutrinos and antineutrinos owing to it’s ability to identify the charge of the associated leptons because of the magnetic field. The major physics goals of INO includes - re-confirmation of atmospheric neutrino oscillations using neutrinos and antineutrinos separately, measuring atmospheric neutrino oscillation parameters with improved precision, determination of the neutrino mass hierarchy using matter effects exploiting the charge identification capability of the detector, to measure the deviation of the 2-3 mixing angle from maximal value and determine its octant, to explore CP violation in the lepton sector, to test new physics scenarios like CPT violation, non-standard interactions etc. using atmospheric neutrinos. Apart from this the ICAL detector can also be used for indirect search of dark matter, magnetic monopole searches etc. In this talk I will present the preliminary results on the potential of the detector to determine mass hierarchy, $\delta_{\text{CP}}$, precision of atmospheric parameters and octant of $\theta_{23}$.

The broader goal of INO is to build an underground laboratory for science with neutrino physics as the major activity and apart from the ICAL detector there are also plans of building detectors for neutrinoless double beta decay and detection of dark matter. With nearly 100
scientists from 23 Institutes and Universities all over India being involved, the INO project is one of the largest basic science projects in India in terms of man power and money.

2. INO site
The site for construction of the observatory is located in Bodi west hills, in Pottipuram village of Theni district in Tamilnadu in the southern part of India. The land area is 26.8 Ha. The climatic conditions are conducive since this is a warm low rain-fall and low humidity area through out the year. The terrain is flat with good access to major roads. The nearest airport is in Madurai city which is situated at a distance of 110 km. The underground laboratory will have three caverns. The Cavern-1 will be set under a 1589 m peak with a vertical rock cover of 1289 m which will be accessible through a 1.9 km long tunnel. It will host the 50 kt detector and there will be space for another 50 kt detector. Cavern 2 and 3 will host other experiments like neutrinoless double beta decay, dark matter etc. The INO collaboration obtained the financial approval from the Government of India in 2014. 13 Ha of land has also been allotted at the Madurai city for the construction of Inter-institutional Centre for High Energy Physics (ICHEP). This will be a surface laboratory where an engineering module of the ICAL detector will be built. However the collaboration is still awaiting the environmental clearance from the Tamilnadu state Government and all construction work at Madurai and Theni are on hold at the moment.

3. ICAL@INO
The proposed detector, ICAL, will be made up of 50 kt iron and will have a modular structure. The choice of iron as a detector material is motivated by its high Z value so that the detector can be compact. Apart from that it allows the possibility of magnetization which in turn enables one to identify the charge of the final state leptons. The dimension of each module is 16m × 16m × 14.4m resulting in a total detector dimension of 48 m × 16m × 14.4m for three modules. Each module consists of 151 horizontal layers of iron plates interleaved with the active detector elements which are the Resistive Plate Chambers (RPC). Each iron plate has thickness of 5.6 cm with a 4cm gap between them for the RPC trays. Each RPC has dimension 2m × 2m and is made up of 3 mm glass plates with 2 mm spacers. The RPCs will be operated at a high voltage of ~10kV in the Avalanche mode. The signals of high energy charged particles passing through the RPC will be read by the orthogonal X and Y pick up strips on both sides of the RPC. Each strip has 3 cm width. This will provide the X and Y coordinates of the track of the charged particles while the layer number will provide the Z coordinate. The timing resolution of the RPCs is 1 ns which enables one to distinguish between the upgoing and downgoing atmospheric neutrinos. Each module will contain two vertical slots for placing current carrying copper coils which will be wound around the detector. The copper coils will carry direct current which will be used to magnetize the iron plates. Simulation of magnetic field shows that 1 T Magnetic field can be reached in about 85% of the detector volume with the maximum field reaching up to 1.5 T. With a mass of 50 kt ICAL will be the world’s largest electromagnet.

Atmospheric muon neutrinos produce muons and hadrons in the detector via charge current interactions. The muon generates a track, and hadrons are associated with showers. The energy of the muon can be measured from the track length or the curvature of the track in the magnetic field. The direction of the muon can be determined from the track. This is helped by the nano second timing resolution of the RPCs. Charge identification is done from track curvature in magnetic field.

The research and development activities are underway at various participating institutions. A prototype RPC stack is operational at TIFR, Mumbai since last six years. Now this system is being used for developing and testing ICAL electronics. A 35 ton prototype magnet and RPC set up has been developed in VECC, Kolkata. Both glass and Bakelite RPCs have been tested in this set up. Full size (2m × 2m) RPCs are being fabricated in the participating INO institutes.
Figure 1. The left panel shows the momentum resolution of muons for different zenith angles \[1\]. The right panel gives the energy resolution of hadrons using NUANCE generated events. The horizontal error bars represent the bin width \[2\].

and the process of large scale industrial production has been initiated. A 12 layer stack of \(2m \times 2m\) RPCs is working at Madurai. Electronics, trigger and data acquisition systems are in their final stages of development.

4. Physics and Simulation

The atmospheric neutrino events are generated with the NUANCE \[3\] neutrino generator. The output gives the different reaction channels, vertex information and the energy and momentum of all the final state particles. Detailed simulations of the ICAL detector performance have been accomplished using the GEANT4 \[4\] package. At this stage the outputs are the \((x,y,z,t)\) coordinates of the particles as they pass through the detector, the energy deposited and the momentum information. The next stage is digitization including the noise and detector efficiency. Finally the event reconstruction is done using Kalman filter techniques to reconstruct the muon energy and momentum. It is also possible to reconstruct the hadrons in ICAL using the hit information in the shower — the number of hits giving information on energy and the position of the hits giving the information on the direction. The Fig. 1 shows the response of the detector to the muons and hadrons. From the left-panel we see that that the muon energy resolution depends on the zenith angle. Typical values are 25% (12%) at 1 GeV (20 GeV), as can be seen from the left panel of Fig. 1 \[1\]. The reconstruction efficiency for muons with energies above 2 GeV is more than 80% and the charge identification efficiency is more than 95%. At high energies, the muon direction resolution is better than a degree \[1\]. The energy resolution of the hadrons is found to be about 85% (36%) at 1 GeV (15 GeV) \[2\] as shown in Fig. 1 (right panel). Note that hadron reconstruction is a special feature of the ICAL detector. Knowing the muon and hadron energy and direction will allow the reconstruction of neutrino energy and direction in principle. More work in this direction is in progress.

For the physics analysis, a large number (typical exposure \(\sim 1000\) years) of unoscillated events are generated using NUANCE. These events are later scaled to the exposure under consideration. The effects of oscillations are included via a reweighting algorithm. The Honda 3d fluxes \[5\] for the Kamioka site in Japan are used in the simulation. A preliminary comparison with the Theni fluxes at the two sites show that for energies above 3 GeV the number of muon events are similar, within statistical errors.

Figure 2 shows the mass hierarchy sensitivity as a function of time for the 50 kt ICAL detector assuming NH (left panel) and IH (right panel) as the true mass hierarchy. The true values of the
oscillation parameters are fixed as (here and in the rest of the draft, unless otherwise mentioned)
\(\Delta m_{21}^2 = 2.4 \times 10^{-3} \text{ eV}^2\), \(\sin^2 \theta_{23} = 0.5\), \(\Delta m_{32}^2 = 7.8 \times 10^{-5} \text{ eV}^2\), \(\sin^2 \theta_{12} = 0.31\) and \(\delta_{CP} = 0\). The \(\chi^2\) analysis is performed using the methods of pulls. The uncertainties in the parameter values are included in the analysis by including a \(\chi^2_{\text{prior}}\). More details of the analysis can be found in [6]. The black dashed curves are obtained for an analysis using the information on muon energy and direction [7]. The red solid curves show the results including the correlated information on hadron energy in each event. For this analysis the binning is done in the 3-dimensional parameter space in the variables: \((E_\mu, \cos \theta_\mu, E_\text{had}')\). A comparison of the plots for the true NH case shows that for the muon only (binning in \((E_\mu, \cos \theta_\mu)\)) or 2D analysis \(\Delta \chi^2_{\text{ICAL-MH}} \approx 6.5\) is obtained with 10 years of exposure for \(\sin^2 \theta_{23} = 0.5\) and \(\sin^2 2\theta_{13} = 0.1\). Including the hadron energy information i.e for the 3D analysis \(\Delta \chi^2_{\text{ICAL-MH}} \approx 9.5\) [8] can be achieved. Thus introducing the 3D binning scheme results in a substantial improvement in the mass hierarchy sensitivity. A larger (smaller) significance is obtained for higher (lower) values of the mixing angles \(\theta_{23}\) and \(\theta_{13}\).

![Figure 2](image)

**Figure 2.** The marginalized mass hierarchy sensitivity of ICAL for true mass hierarchy normal (left) and inverted (right) incorporating the correlated hadron energy information [8]. The improvement with the inclusion of hadron energy is visible.

In Fig. 3 we show the combined mass hierarchy sensitivity of ICAL and beam based experiments T2K and NO\(\nu\)A. The mass hierarchy sensitivity of beam based experiments depends on the true value of \(\delta_{CP}\) and is low for \(\delta_{CP} = 0\). However if one adds the ICAL data along with that of T2K and NO\(\nu\)A then even for \(\delta_{CP} = 0\), 3\(\sigma\) sensitivity to mass hierarchy can be obtained in 6 years by the 50 kt detector for the case of maximal mixing. This can be seen from Fig. 3.

The mass hierarchy sensitivity of ICAL can also be useful for the determination of \(\delta_{CP}\) although ICAL itself does not have any sensitivity to \(\delta_{CP}\). This happens as for certain values of CP phases (depending on the true mass hierarchy) the CP sensitivity of NO\(\nu\)A or T2K experiment is not very high because of the presence of wrong hierarchy-wrong CP solutions. The mass hierarchy sensitivity from ICAL data helps to remove these wrong hierarchy solutions. Hence a combined analysis of T2K+NO\(\nu\)A+ICAL results in an enhanced CP sensitivity [9]. This is shown in Fig. 4 where we plot the CP discovery (i.e ability to differentiate a true \(\delta_{CP}\) value from 0 or 180\(^\circ\)) \(\chi^2\) vs true value of \(\delta_{CP}\). The figure shows that adding ICAL data improves the CP discovery potential of T2K+NO\(\nu\)A in the range 0 < \(\delta_{CP} < 180^\circ\) (180\(^\circ\) < \(\delta_{CP} < 360^\circ\)) for NH(IH).

In Fig. 5, we present the sensitivity of ICAL to the parameters \(\sin^2 \theta_{23}\) and \(|\Delta m_{32}^2|\) for the true mass hierarchy as NH. The undisplayed parameters are marginalized over. Similar results
Figure 3. Hierarchy sensitivity for true NH (left) and IH (right) by combining 50 kt ICAL data with the simulated data from T2K (total luminosity of $8 \times 10^{21}$ pot in neutrino mode) and NOνA (running 3 years in neutrino and 3 years in antineutrino mode) [6].

Figure 4. CP discovery $\chi^2$ vs true $\delta_{cp}$ for NOνA+T2K and NOνA+T2K+ICAL (500 kt-yr exposure), for $\theta_{23}(\text{true})= 39^\circ$ for true mass hierarchy as NH (IH) in left (right) panels; $\sin^2 2\theta_{13} = 0.1$ with a prior of $\sigma_{\theta_{13}} = 0.005$ [6].

are obtained for true IH. It is evident from the figure that the inclusion of the hadron information improves the precision as compared to muon-only analysis.

The octant sensitivity of the ICAL detector has also been studied with and without including the hadron energy information [8]. It was found that a 2σ discovery of the octant is possible with the 500 kt-yr NO data when the true mass hierarchy is NH and the true octant is lower. From the analysis, including hadron energy bins, octant discovery is possible for $\sin^2 2\theta_{23}(\text{true}) < 0.395$. If the true octant is higher or the true mass hierarchy is inverted, then the capability of only ICAL data in determining the octant of $\theta_{23}$ is poor. A combination of ICAL and long baseline experiments like T2K and NOνA can give enhanced octant sensitivity [10].

Recently the oscillation analysis of ICAL has been performed by including muons in the energy range 0.5-25 GeV (as compared to the range 1-11 GeV in the earlier analyses) and adding an extra pull as a constraint on $\Phi_{\nu_{\mu}}/\Phi_{\bar{\nu}_{\mu}}$ ratio [11]. It was found that the precision on the parameters $\sin^2 \theta_{23}$ and $|\Delta m^2_{32}|$ as well as the mass hierarchy sensitivity increases by including the high energy muons. Addition of the new pull helps in increasing the precision of
\[ \sin^2 \theta_{23}. \]

5. Concluding Remarks

INO has a very strong physics programme using atmospheric neutrinos. It is the only atmospheric neutrino detector which will have charge identification capability and hence will be able to separate atmospheric neutrino induced muons from the anti-muons. This gives it an edge to determine the mass hierarchy using the Earth matter effect which is different for NH and IH and neutrinos and antineutrinos.

The INO collaboration has made considerable progress on all fronts. The detector design has been finalized and characterization of RPCs have been completed. Industrial manufacture of RPCs have also been initiated. Electronics, trigger, data acquisition systems are also in their final stage of prototyping. The simulation packages are being developed and the Physics White Paper containing the first set of results have been published [6]. In conclusion, the INO physics program is all set to contribute to the worldwide activity in neutrino physics.

6. Acknowledgement

I would like to thank the INO collaboration specially V. Datar, A. Dighe, C. Gupta, N. Mondal, L.S. Mohan for their help in preparing the talk.

References

[1] A. Chatterjee et al., JINST 9 (2014) P07001.
[2] M. M. Devi et al., JINST 8 (2013) P11003.
[3] D. Casper, Nucl. Phys. Proc. Suppl. 112 (2002) 161.
[4] S. Agostinelli et al. [GEANT4 Collaboration], Nucl. Instrum. Meth. A 506 (2003) 250.
[5] M. Honda, T. Kajita, K. Kasahara and S. Midorikawa, Phys. Rev. D 83 (2011) 123001.
[6] S. Ahmed et al. [ICAL Collaboration], arXiv:1505.07380 [physics.ins-det].
[7] A. Ghosh, T. Thakore and S. Choubey, JHEP 1304 (2013) 009.
[8] M. M. Devi, T. Thakore, S. K. Agarwalla and A. Dighe, JHEP 1410 (2014) 189.
[9] M. Ghosh, P. Ghoshal, S. Goswami and S. K. Raut, Phys. Rev. D 89 (2014) no.1, 011301.
[10] A. Chatterjee, P. Ghoshal, S. Goswami and S. K. Raut, JHEP 1306 (2013) 010.
[11] L. S. Mohan and D. Indumathi, arXiv:1605.04185 [hep-ph].