Physics potential of INO-ICAL

Amol Dighe
TIFR, Mumbai, India
(For the INO-ICAL Collaboration)

Workshop on neutrino programs with facilities in Japan, Aug 4-6th, 2015
Some good news started this year...

Press Release

The Union Cabinet of the Govt. of India chaired by the Prime Minister, Shri Narendra Modi, has given its approval for the establishment of India-based Neutrino Observatory (INO) at an estimated cost of Rs. 1500 crores.

The INO project is jointly supported by the Department of Atomic Energy and the Department of Science and Technology. Infrastructural support is provided by the Government of Tamil Nadu where the project is located. Tata Institute of Fundamental Research (TIFR), Mumbai is the host institute for INO.

But there is a long way to go.....
Physics potential of INO-ICAL

Physics Potential of the ICAL detector at the India-based Neutrino Observatory (INO)

The ICAL Collaboration

The location of INO

Bodi West Hills,
Pottipuram Village,
(100 km from Madurai)
Tamil Nadu State
The cavern
ICAL Modules in the main cavern
The ICAL detector: desiderata

- **Large target mass** *(50 – 100 kt)*
- **Good tracking and Energy resolution** *(Tracking calorimeter)*
- **Good directionality for up/down discrimination** *(Nano-second time resolution)*
- **Charge identification capability** *(uniform, homogeneous magnetic field)*
- **Ease of construction & Modularity**
- **Complementarity to the other existing / proposed detectors**
The ICAL detector

- 5.6 cm thick iron plate
- 4 cm air gap for RPC detector
The magnetic field
The active detector: RPC
The detector specifications

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>No of modules</td>
<td>3</td>
</tr>
<tr>
<td>Module dimension</td>
<td>16 m X 16 m X 14.4m</td>
</tr>
<tr>
<td>Detector dimension</td>
<td>48.4 m X 16 m X 14.4m</td>
</tr>
<tr>
<td>No of layers</td>
<td>150</td>
</tr>
<tr>
<td>Iron plate thickness</td>
<td>5.6cm</td>
</tr>
<tr>
<td>Gap for RPC trays</td>
<td>4 cm</td>
</tr>
<tr>
<td>Magnetic field</td>
<td>1.4 Tesla</td>
</tr>
<tr>
<td>RPC unit dimension</td>
<td>195 cm x 184 cm x 2.4 cm</td>
</tr>
<tr>
<td>Readout strip width</td>
<td>3 cm</td>
</tr>
<tr>
<td>No. of RPCs/Road/Layer</td>
<td>8</td>
</tr>
<tr>
<td>No. of Roads/Layer/Module</td>
<td>8</td>
</tr>
<tr>
<td>No. of RPC units/Layer</td>
<td>192</td>
</tr>
<tr>
<td>Total no of RPC units</td>
<td>28800</td>
</tr>
<tr>
<td>No of Electronic channels</td>
<td>$3.7 \times 10^6$</td>
</tr>
</tbody>
</table>
Atmospheric neutrino flux

Averaged over all directions
Summed over all flavors of neutrino and anti-neutrino

Horizontal component of the geomagnetic field
Magnitude at the Earth’s surface ranges from 25 to 65 microtesla

Angular distribution of neutrino flux


Physics potential of INO-ICAL
## Simulation framework

| NUANCE | Neutrino Event Generation $\nu_\ell + N \rightarrow \ell + X$. Generates particles that result from a random interaction of a neutrino with matter using theoretical models for both neutrino fluxes and cross-sections. | Output:  
(i) Reaction Channel  
(ii) Vertex and time information  
(iii) Energy and momentum of all final state particles |
| --- | --- | --- |
| GEANT | Event Simulation $\ell + X$ through simulated ICAL. Simulates propagation of particles through the ICAL detector with RPCs and magnetic field. | Output:  
(i) $x, y, z, t$ of the particles as they propagate through detector  
(ii) Energy deposited  
(iii) Momentum information |
| DIGITISATION | Event Digitisation $(X, Y, Z, T)$ of final states on including noise and detector efficiency. Add detector efficiency and noise to the hits. | Output:  
(i) Digitised output of the previous stage |
| ANALYSIS | Event Reconstruction $(E, p)$ of $\ell, X$ (total hadrons). Fit the muon tracks using Kalman filter techniques to reconstruct muon energy and momentum; use hits in hadron shower to reconstruct hadron information. | Output:  
(i) Energy and momentum of muons and hadrons, for use in physics analyses. |
Event distribution (NUANCE)

Relative contributions of three cross-section processes to the total events in the absence of oscillation and without detector efficiency and resolutions.
Inelasticity distribution

Inelasticities in individual events have a wide distribution

Important to measure inelasticity in individual events
A typical CC event in ICAL

Using GEANT4 simulation
Detector response to muons

- **Energy Resolution**
  - Graph showing the ratio of $\frac{E_{\mu}}{E_{\mu}}$ as a function of $E_{\mu}$ (GeV) for different values of $\cos \theta_{\mu}$.

- **Angular Resolution**
  - Graph showing the distribution of $\sigma_{\cos \theta_{\mu}}$ as a function of $E_{\mu}$ (GeV) for different values of $\cos \theta_{\mu}$.

- **Detection Efficiency**
  - Graph showing the reconstruction efficiency as a function of $E_{\mu}$ (GeV) for different values of $\cos \theta_{\mu}$.

- **Charge ID**
  - Graph showing the charge identification efficiency as a function of $E_{\mu}$ (GeV) for different values of $\cos \theta_{\mu}$.

Physics potential of INO-ICAL
Detector response to hadrons

\[ E_h = E_v - E_\mu \text{ (from hadron hit calibration)} \]

Hadron energy resolution: 85% at 1 GeV and 36% at 15 GeV

Typical analysis technique

We define the Poissonian $\chi^2$ for $\mu^-$ events as:

$$\chi^2 = \min_{\xi_l} \sum_i \sum_j \sum_k \left[ 2(N_{ij}^{\text{theory}} - N_{ij}^{\text{data}}) - 2N_{ij}^{\text{data}} \ln \left( \frac{N_{ij}^{\text{theory}}}{N_{ij}^{\text{data}}} \right) \right] + \sum_{l=1}^{5} \xi_l^2,$$

where

$$N_{ij}^{\text{theory}} = N_{ij}^0 \left(1 + \sum_{l=1}^{5} \pi_{ij}^l \xi_l \right).$$

1) Overall 5% systematic uncertainty
2) Overall flux normalization: 20%
3) Overall cross-section normalization: 10%
4) 5% uncertainty on the zenith angle dependence of the fluxes
5) Energy dependent tilt factor:
   $\Phi_0(E) = \Phi_0(E) \left[ E/E_0 \right]^{\delta} \approx \Phi_0(E) \left[ 1 + \delta \ln E/E_0 \right]$
   where $E_0 = 2$ GeV and
   $\delta$ is the 1σ systematic error of 5%
Importance of hadron information

Distribution of \((\Delta \chi^2 / \text{area}) [\chi^2 (\text{IH}) - \chi^2 (\text{NH})]\) for mass hierarchy discrimination considering \(\mu^-\) events

Hadron energy information not used

Hadron energy information used
Mass hierarchy sensitivity: ICAL alone

MH sensitivity dependence on mixing angles


50 kt ICAL can rule out the wrong hierarchy with median $\Delta \chi^2 \approx 7$ to 12 depending on the true values of $\theta_{23}$ and $\theta_{13}$ in 10 years
Synergy with T2K and NOvA (at deltaCP=0)

Physics potential of INO-ICAL

3σ median sensitivity can be achieved in 6 years (deltaCP=0)

Thakore, Agarwalla, work in progress
Synergy at other DeltaCP values

ICAL works even in the "unlucky" deltaCP range....
Sensitivity to atmospheric mixing parameters

Significant improvement in the precision measurement of atmospheric mass splitting by adding hadron energy information with muon momentum
Reach for atmospheric mixing parameters

Physics potential of INO-ICAL
Octant sensitivity

Median 2σ discovery of θ_{23} octant is possible if θ_{23} is sufficiently away from maximal value
Other analyses in progress

- Search for sterile neutrinos
- CPT violation and Non-Standard Interactions
- Search for magnetic monopoles
- Search for dark matter from the Sun
- Long range forces
- Exploiting NC events
- Possibilities of electron detection

........
Current status of INO project

• Site infrastructure development

• Development of INO centre at Madurai city (110 km from underground lab)
  - Inter-Institutional Centre for High Energy Physics (IICHEP)

• Construction of an 8m x 8m x 2.1 m engineering prototype module

• Detector R&D is now over

• Detailed Project Report for Detector and DAQ system is ready

• Soon go for industrial production of RPCs & associated front-end electronics
Prototype: the next step

Water cooled copper conductor
The prospects

• Good muon tracking, charge ID and sensitivity to multi-GeV hadrons makes ICAL a unique multi-purpose detector
• Sensitive primarily to mass hierarchy, but also to many other new physics possibilities
• Synergy with ongoing and upcoming long baseline experiments
• Waiting for final go-ahead to start making the tunnel (t=0)
• The first module expected to start taking data at t=5 years
Thank You

• Collaborators are welcome...

http://www.ino.tifr.res.in/ino
nkm@tifr.res.in  (Naba Mondal, Spokesperson)