Precision measurement of neutrino oscillation parameters @ INO-ICAL Detector

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Outline

1. Introduction
2. INO Experiment
3. Neutrino Interaction
4. Analysis Performed
5. Inputs for analysis
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7. Conclusions
Neutrinos are chargeless, spin 1/2, very weakly interacting, tiny mass particle which comes in three active flavors $\nu_e$, $\nu_\mu$ and $\nu_\tau$.

Standard Model of particle physics predicts that the neutrinos are massless but the strong and compelling evidences from several experiments show that neutrinos have masses and they oscillate.

The phenomenon of flavor changing among the neutrinos is called Neutrino Oscillation.
Neutrino Oscillation ⇔ Neutrino are massive and mixed

The relation between flavor and mass eigen state as:

$$|\nu_\alpha\rangle = \sum_i U_{\alpha i}^* |\nu_i\rangle$$

where $\alpha$ is the flavor (e, $\mu$ or $\tau$) and $i=1, 2, 3$ denotes the neutrino mass eigen state. $U_{\alpha i}$’s are the matrix elements of PMNS mixing matrix U.

Probability of flavor change is:

$$P(\nu_\alpha \rightarrow \nu_\beta) = \delta_{\alpha\beta} - 4 \sum_{i>j} \Re(U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*) \sin^2[1.27 \Delta m^2_{ij} (L/E)]$$

$$+ 2 \sum_{i>j} \Im(U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*) \sin[2.54 \Delta m^2_{ij} (L/E)]$$

Where $\Delta m^2_{ij} = m_i^2 - m_j^2$ in eV$^2$, L in Km and E in GeV.

- $\alpha = \beta$ Survival probability, $\alpha \neq \beta$ Transition probability
- requires $U \neq 1$ and $\Delta m^2_{ij} \neq 0$
Two flavor Neutrino Oscillation in vacuum

The mixing matrix is:

\[ U = \begin{bmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{bmatrix} = \begin{bmatrix} U_{\alpha 1} & U_{\alpha 2} \\ U_{\beta 1} & U_{\beta 2} \end{bmatrix} \]  \tag{1} \]

where \( \theta \) is the mixing angle.

The transition probability is given as:

\[ P_{\alpha \beta} = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right) \]  \tag{2} \]

where \( L \) is the baseline and \( E \) is the energy of the neutrino.
Open Questions: Neutrino Physics

- What is the right order of neutrino mass spectrum?
- What is the right octant for mixing angle $\theta_{23}$?
- What is the value of CP phase delta?
- Precision measurement of neutrino oscillation parameters.

Mass Hierarchy of Neutrinos

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ν_e  ν_μ  ν_τ
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“Normal” Hierarchy  “Inverted” Hierarchy
The INO Experiment

The India-based Neutrino Observatory (INO) is a planned proposal for studying the properties of atmospheric neutrinos using a magnetised Iron CALorimeter detector (ICAL).

A large cavern of dimension 170m x 20m x 32m will be constructed to place the detector under the mountain at Theni (Tamilnadu) in South India.

Precision measurement of atmospheric neutrino oscillation parameters and the determination of neutrino mass hierarchy are the main aims of INO-ICAL experiment.

The ICAL has a special feature to detect the neutrino and anti-neutrino from the bending of the associative leptons and anti-leptons in an applied magnetic field.
The INO-ICAL Detector

ICAL specifications

1. Total Mass : $\sim 50$ ktons
2. Dimension : $16 \text{m} \times 16 \text{m} \times 14.5 \text{m}$ (for one module)
3. Target : Iron (5.6 cm thick)
4. Active Material : Resistive Plate Chambers (RPCs) of $2 \text{m} \times 2 \text{m}$ dimension
5. Magnetic field : $\sim 1.5 \text{T}$

Resistive Plate Chamber (RPC)

- Gaseous detector
- Two dimensional output
- Cheap and Best
- Efficiency $> 95\%$ at high voltage ($\sim 10 \text{kV}$)
- Good spatial ($\sim 3 \text{ cm}$) and time resolution ($\sim 1 \text{ns}$)
ICAL is sensitive to atmospheric muon neutrinos ($\nu_\mu, \bar{\nu}_\mu$)

Cosmic ray interactions with the earth atmosphere produces Pions.

$$\pi^+ \rightarrow \mu^+ \nu_\mu \quad \mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$$

$$\pi^- \rightarrow \mu^- \bar{\nu}_\mu \quad \mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$$

Down going $\rightarrow$ near detector $\Rightarrow$ No oscillations
Up coming $\Rightarrow$ Far detector $\Rightarrow$ Oscillations

Single detector with equal source.

$$\frac{N(\text{up})}{N(\text{down})} = \frac{L}{E}$$

Ratio of up and down going events will reflect the Asymmetry of up-down fluxes, due to oscillation

$\Rightarrow$ Direct measurement of oscillation probability
Neutrino Interactions with ICAL detector

- Neutrino Interacts weakly via Charge Current (CC) and Neutral Current (NC) process
- Atmospheric muon neutrino interact with the ICAL detector and produce associative lepton and hadron shower
- For muon neutrino, the energy of neutrino ($E_\nu$) will be the sum of muon energy ($E_\mu$) and hadron energy ($E_{hadron}$)
- To reconstruct the energy and direction of neutrino, energy and direction of muons and hadrons need to be reconstructed precisely
- Muon can be identified and reconstructed easily with their clear tracks and bending inside the detector.
- The energy of hadrons can be calibrated as a function of shower hits.
Hadron Energy Resolution


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![Diagram of muon track and hadron shower](image1)

- $E_v = 14.3$ GeV
- $E_\mu = 3.71$ GeV
- $E_{had} = 10.59$ GeV

![Histogram of charged pions](image2)

- 1 GeV
- 2 GeV
- 5 GeV
- 10 GeV
- 15 GeV

- $\chi^2 / \text{ndf} = 165.7 / 55$
- $a = 0.863 \pm 0.005$
- $b = 0.279 \pm 0.002$

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![Plot of mean number of hits vs $E_\pi$](image3)

- $\pi^\pm$ events
- Data points
- Linear fit

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![Plot of $\sigma/E$ vs $E_\pi$](image4)
Muon Energy and Direction Resolutions

(a) Muon energy Resolution

(b) $\cos \theta_\mu$ Resolution

(c) Reconstruction efficiency for muons

(d) Charge identification efficiency for muons
Precise measurement of atmospheric $\nu$ oscillation parameters ($|\Delta m^2_{32}|$, $\sin^2 \theta_{23}$) is one of the major goal of INO-ICAL detector.

For INO-ICAL sensitivity for these parameters, we have performed a Monte Carlo based neutrino event simulation.

We have performed the analysis using Neutrino energy ($E_\nu = E_\mu + E_{hadron}$) and Muon angle ($\cos \theta_\mu$) observables.
1000 years unoscillated data generated from NUANCE generator is used as input which is then scaled for 10 years exposure of running ICAL detector.

For the analysis both $\nu_\mu \rightarrow \nu_\mu$ and $\nu_e \rightarrow \nu_\mu$ channels are considered.

Only Charged-current (CC) events are considered for the analysis.

To introduce the oscillation effect, Re-weighting algorithm based on Monte Carlo acceptance/rejection method has been used.

Energy and angular resolutions, Reconstruction and Charge id efficiencies are used as generated by INO Collaboration.

Energy Binning : 0.8-10.8 GeV with 10 equal bins

$\cos \theta$ Binning : -1 to 1 with 20 equal bins

Random number smearing is applied both for expected and observed events.
For $\nu_\mu \rightarrow \nu_\mu$ channel:

1. For an unoscillated $\nu_\mu$ event of energy $E$ and zenith angle $\theta_z$, probabilities $P_{\nu_\mu \nu_e}$, $P_{\nu_\mu \nu_\tau}$ and $P_{\nu_\mu \nu_\mu}$ are calculated.
2. A uniform random number ($r$), between 0 and 1 is associated with every interaction in NUANCE data without oscillations.
3. If $r < P_{\nu_\mu \nu_e}$, the event is considered as a $\nu_e$ event.
   If $P_{\nu_\mu \nu_e} \leq r \leq (P_{\nu_\mu \nu_e} + P_{\nu_\mu \nu_\mu})$, the event is considered as a $\nu_\mu$ event.

For $\nu_e \rightarrow \nu_\mu$ channel:

1. Atmospheric $\nu_e$ may also change flavor to $\nu_\mu$ due to oscillations.
2. We calculate the transition probability ($P_{\nu_e \nu_\mu}$) for each event.
3. A random number ($r'$), uniformly distributed in [0,1] is associated with every event.
4. If $r' < (P_{\nu_e \nu_\mu})$, we considered the event as a $\nu_\mu$ event.
### Oscillation parameters

<table>
<thead>
<tr>
<th>Oscillation parameters</th>
<th>True values</th>
<th>Marginalisation range</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sin^2(2\theta_{12})$</td>
<td>0.86</td>
<td>Fixed</td>
</tr>
<tr>
<td>$\sin^2 \theta_{23}$</td>
<td>0.5</td>
<td>0.4-0.6 (3\sigma range)</td>
</tr>
<tr>
<td>$\sin^2 \theta_{13}$</td>
<td>0.03</td>
<td>0.01 (3\sigma range)</td>
</tr>
<tr>
<td>$\Delta m_{21}^2 (eV^2)$</td>
<td>7.6 $\times$ 10$^{-5}$</td>
<td>Fixed</td>
</tr>
<tr>
<td>$\Delta m_{32}^2 (eV^2)$</td>
<td>2.4 $\times$ 10$^{-3}$</td>
<td>(2.1-2.6) $\times$ 10$^{-3}$ (3\sigma range)</td>
</tr>
<tr>
<td>$\delta_{CP}$</td>
<td>0.0</td>
<td>Fixed</td>
</tr>
</tbody>
</table>

**Table:** Oscillation parameters used for analysis.

Marginalisation over the $\sin^2 \theta_{23}$ and $\Delta m_{32}^2 (eV^2)$ has been done for the 1D $\chi^2$ plots only.
Theoretical probabilities for neutrinos at $L=9700\text{Km.}$

<table>
<thead>
<tr>
<th>Energy (GeV)</th>
<th>$P_{\mu\mu}$ in vacuum</th>
<th>$P_{\mu\mu}$ in NH</th>
<th>$P_{\mu\mu}$ in IH</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.2</td>
<td>0.4</td>
<td>0.6</td>
</tr>
<tr>
<td>2</td>
<td>0.4</td>
<td>0.6</td>
<td>0.8</td>
</tr>
<tr>
<td>3</td>
<td>0.6</td>
<td>0.8</td>
<td>1</td>
</tr>
</tbody>
</table>

For antiNeutrinos, $L\sim9700\text{Km.}$

<table>
<thead>
<tr>
<th>Energy (GeV)</th>
<th>$P_{\bar{\mu}\bar{\mu}}$ in vacuum</th>
<th>$P_{\bar{\mu}\bar{\mu}}$ in NH</th>
<th>$P_{\bar{\mu}\bar{\mu}}$ in IH</th>
</tr>
</thead>
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<tr>
<td>1</td>
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<td>0.4</td>
<td>0.6</td>
<td>0.8</td>
</tr>
<tr>
<td>3</td>
<td>0.6</td>
<td>0.8</td>
<td>1</td>
</tr>
</tbody>
</table>

Figure: Oscillation probabilities $P(\nu_\mu \rightarrow \nu_\mu)$ (left) and $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu)$ (right) in vacuum (Blue), matter for normal hierarchy (Green) and inverted hierarchy (Red) ($L\sim9700\text{ Km.}$)
Figure: The $\mu^-$ events for the muon energy range 1.8 - 2.8 GeV in the absence (Red) and in the presence (Blue) of oscillations (left) and in presence of INO resolutions and efficiencies (Green), for 10 years of exposure of ICAL detector.
Poissonian $\chi^2$ (using method of “Pull”)$^\dagger$ is defined as:

$$\chi^2(\nu_\mu) = \sum_{i,j} \left( 2(N_{i,j}^{th}(\nu_\mu) - N_{i,j}^{ex}(\nu_\mu)) + 2N_{i,j}^{ex}(\nu_\mu)(\ln \frac{N_{i,j}^{ex}(\nu_\mu)}{N_{i,j}^{th}(\nu_\mu)}) \right) + \sum_k \zeta_k^2 \tag{3}$$

$$N_{i,j}^{th}(\nu_\mu) = N_{i,j}^{th'}(\nu_\mu) \left( 1 + \sum_k \pi_{i,j}^{k} \right) \tag{4}$$

- $N_{i,j}^{ex}$ ≡ Observed number of the $\nu_\mu$ events in $(i = E_\nu, j = \cos \theta_\mu)$ bin generated using true values of the oscillation parameters.
- $N_{i,j}^{th'}$ ≡ Theoretically predicted events generated by varying oscillation parameters (without systematic effects).
- $N_{i,j}^{th}$ ≡ Shifted events spectrum due to different systematic uncertainties.

Above $\chi^2$ is minimised as a function of pull variable $\zeta$ and the oscillation parameters ($\Delta m^2_{32}$, $\sin^2 \theta_{23}$).

• We have calculated the $\chi^2(\nu_\mu)$ and $\chi^2(\bar{\nu}_\mu)$ separately.

• Final $\chi^2$ is defined as:

$$\chi^2_{ino} = \chi^2(\nu_\mu) + \chi^2(\bar{\nu}_\mu)$$  \hspace{1cm} (5)

• **Prior on $\theta_{13}$:**

$$\chi^2 = \chi^2_{ino} + \left( \frac{\sin^2 \theta_{13}(true) - \sin^2 \theta_{13}}{\sigma_{\sin^2 \theta_{13}}} \right)^2$$  \hspace{1cm} (6)

• For the analysis $\sigma_{\sin^2 \theta_{13}}$ is taken as 10% of the true value of $\sin^2 \theta_{13}$

• Finally, we obtain the contour plots assuming $\Delta \chi^2 = \chi^2 + m$, where values of $m$ are taken as 2.30, 4.61 and 9.21 corresponds to 68%, 90% and 99% confidence levels
Systematic uncertainties considered the analysis are:

1. 20% overall flux normalisation uncertainty
2. 10% cross-section uncertainty
3. 5% overall statistical uncertainty
4. 5% uncertainty on the zenith angle dependence of the flux. This error is calculated by taking 5% of the mean value of each $\cos \theta_\mu$ bin
5. 5% an energy dependent tilt error.

![Effect of systematics (90% CL)](image-url)
Figure: 1D plot for the sensitivity of $|\Delta m_{\text{eff}}^2|$ at constant $\sin^2 \theta_{23} = 0.5$ (left) and for the sensitivity of $\sin^2 \theta_{23}$ as a function of $\Delta \chi^2$ at constant $\Delta m_{31}^2 = 0.0024eV^2$ (right).

This results shows that program is sensitive for $\theta_{23}$ as well as for the sensitivity of $\Delta m_{31}^2$
Figure: Contour plots without systematic errors (Left) and with systematic errors (Right) for 10 years exposure of ICAL
The precision on the oscillation parameters can be defined as:

\[ Precision = \frac{P_{\text{max}} - P_{\text{min}}}{P_{\text{max}} + P_{\text{min}}}, \]  

(7)

where \( P_{\text{max}} \) and \( P_{\text{min}} \) are the maximum and minimum values of the concerned oscillation parameters at the given confidence level.

<table>
<thead>
<tr>
<th>Osc. Parameters</th>
<th>( 1\sigma )</th>
<th>( 2\sigma )</th>
<th>( 3\sigma )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \sin^2 \theta_{23} )</td>
<td>12.7 %</td>
<td>17.40 %</td>
<td>21.08 %</td>
</tr>
<tr>
<td>(</td>
<td>\Delta m^2_{\text{eff}}</td>
<td>)</td>
<td>3.29 %</td>
</tr>
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<tr>
<td>( \sin^2 \theta_{23} )</td>
<td>16.41 %</td>
<td>21.35 %</td>
<td>28.22 %</td>
</tr>
<tr>
<td>(</td>
<td>\Delta m^2_{\text{eff}}</td>
<td>)</td>
<td>3.75 %</td>
</tr>
</tbody>
</table>

Table: ICAL precision measurement of oscillation parameters at different confidence levels for 10 year of exposure.
Conclusions

- Neutrino Oscillation gives a first hint for the physics beyond Standard Model.
- INO-ICAL experiment has been proposed to study the properties of mysterious neutrinos.
- A simulation study has been performed to find the precision measurement of atmospheric neutrino oscillation parameters using realistic ICAL resolutions.
- Final results with Neutrino energy and Muon direction observables have been shown.
- We find that the INO-ICAL can measure $\sin^2 \theta_{23}$ and $|\Delta m^2_{32}|$ with 28.22% and 9.036% uncertainties at 3$\sigma$ confidence level in 10 years of running.

Future Work

- To study the mass heirarchy and Octant sensitivity for INO-ICAL detector
Thank you
Back Up


**Tilt Error** The event spectrum is calculated with the predicted neutrino flux and then with the flux spectrum shifted according to:

\[
\phi_\delta(E) = \phi_0(E) \left( \frac{E}{E_0} \right)^\delta = \phi_0(E) \left( 1 + \delta \ln \frac{E}{E_0} \right)
\]

(8)

where \( E_0 = 2\text{GeV} \) and \( \delta \) is the 1\( \sigma \) systematic error which we have taken as 5\%. The difference between the predicted event spectrum and shifted event spectrum is then included in to statistical analysis.