Standard and Non-Standard Oscillation Physics at ICAL-INO

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S. K. Agarwalla, MITP, Johannes Gutenberg University, Mainz, Germany, 28th July, 2015
Finally the wait of 15 years is over! But, we have miles to go…
Physics Potential of the ICAL detector at the India-based Neutrino Observatory (INO)

The ICAL Collaboration

Plan of this talk:

**Standard Oscillation Physics:**

1) Issue of neutrino mass ordering  
2) Precision measurements of oscillation parameters  
3) Sensitivity to the octant of 2-3 mixing angle

**Non-Standard Oscillation Physics:**

1) Active – Sterile Oscillation  
2) Non-Standard Neutrino Interactions (NSI’s) in propagation
Several 1σ to 1.5σ hints for mass hierarchy

T2K appearance & SK atmospheric data prefers opposite hierarchies

Gonzalez-Garcia, Maltoni, Schwetz, arXiv:1409.5439v2
2-3 Mixing Angle from the Global Fit

For IO, Second Octant is favored around \(1.4\sigma\)

For NO, First Octant is favored around \(1\sigma\)

Gonzalez-Garcia, Maltoni, Schwetz, arXiv:1409.5439v2

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Detector Characteristics

- **Should have 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 (need to have uniform, homogeneous magnetic field)**
- **Ease of construction & Modularity**
- **Complementary to the other existing and proposed detectors**

**Our choice**

**Magnetized iron (target mass): ICAL**

**RPC (active detector element)**

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## Specifications of the ICAL Detector

<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 14.4 m</td>
</tr>
<tr>
<td>Detector dimension</td>
<td>48.4 m X 16 m X 14.4 m</td>
</tr>
<tr>
<td>No. of layers</td>
<td>150</td>
</tr>
<tr>
<td>Iron plate thickness</td>
<td>5.6 cm</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


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Atmospheric Neutrino Flux

E = 3.2 GeV
Averaged over all azimuthal angles

\[ \phi_v \text{ (m}^{-2}\text{ sec}^{-1}\text{ sr}^{-1}\text{ GeV}^{-1}) \]

INo
South Pole
Pyhasalmi


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Matter effect in Atmospheric Experiments

Bands: vary the matter density by ±10%

Atmospheric Conspiracy

Presence of different flavors dilutes the MH effect in oscillation

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Overview of Simulation Framework

NUANCE

**Neutrino Event Generation**
\[ \nu + N \rightarrow \ell + X \]
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.

Simulation work is under progress in full swing!

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Relative contributions of three cross-section processes to the total events in the absence of oscillation and without detector efficiency and resolutions
Average Inelasticity in the deep-inelastic events is significant

Crucial for mass hierarchy identification

Inelasticities in individual events have a wide distribution.

Important to measure inelasticity in individual events.
Event Display Inside the ICAL Detector

Using GEANT4 simulation

Muon Efficiencies and Resolutions

Energy Resolution

Angular Resolution

Detection Efficiency

Charge ID

Reconstruction Efficiency

Charge Identification Efficiency

CC events (without oscillations)

- \( \sigma/E \) in [1GeV - 15GeV]

\[
\frac{\sigma}{E} = \sqrt{\frac{a^2}{E} + b^2}
\]

\( \chi^2 / \text{ndf} = 13.96 / 28 \)

\( a = 0.742 \pm 0.009 \)

\( b = 0.302 \pm 0.004 \)

\( E'_h = E_v - E_\mu \) (from hadron hit calibration)

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

The $\chi^2$ Analysis

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

$$\chi^2_\nu = \min_{\xi_l} \sum_{i=1}^{N_{E_{\text{had}}}} \sum_{j=1}^{N_{E_{\mu}}} \sum_{k=1}^{N_{\cos\theta_{\mu}}} \left[ 2(N^{\text{theory}}_{ijk} - N^{\text{data}}_{ijk}) - 2N^{\text{data}}_{ijk} \ln \left( \frac{N^{\text{theory}}_{ijk}}{N^{\text{data}}_{ijk}} \right) \right] + \sum_{l=1}^{5} \xi^2_l,$$

where

$$N^{\text{theory}}_{ijk} = N^{0}_{ijk} \left( 1 + \sum_{l=1}^{5} \pi^l_{ijk} \xi_l \right).$$

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:
   $$\Phi_\delta(E) = \Phi_0(E) \left[ \frac{E}{E_0} \right]^\delta \approx \Phi_0(E) \left[ 1 + \delta \ln \frac{E}{E_0} \right]$$
   where $E_0 = 2$ GeV and
   $\delta$ is the 1\(\sigma\) systematic error of 5%
Distribution of $\Delta \chi^2 \left[ \chi^2 (\text{IH}) - \chi^2 (\text{NH}) \right]$ for mass hierarchy discrimination considering $\mu^-$ events

- Further subdivide the events into four hadron energy bins
- Hadron energy carries crucial information
- Correlation between hadron energy and muon momentum is very important
<table>
<thead>
<tr>
<th>$E'_{\text{had}}$ (GeV)</th>
<th>events</th>
<th>$\Delta \chi^2$</th>
<th>$\Delta \chi^2$/events</th>
</tr>
</thead>
<tbody>
<tr>
<td>0–1</td>
<td>3995</td>
<td>5.8</td>
<td>0.0014</td>
</tr>
<tr>
<td>1–2</td>
<td>1152</td>
<td>1.9</td>
<td>0.0017</td>
</tr>
<tr>
<td>2–4</td>
<td>742</td>
<td>1.7</td>
<td>0.0023</td>
</tr>
<tr>
<td>4–15</td>
<td>677</td>
<td>1.2</td>
<td>0.0018</td>
</tr>
<tr>
<td>0–15</td>
<td>6566</td>
<td>10.7</td>
<td>0.0016</td>
</tr>
<tr>
<td>(with $E'_{\text{had}}$ information)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>without $E'_{\text{had}}$ information</td>
<td>6775</td>
<td>6.3</td>
<td>0.0009</td>
</tr>
</tbody>
</table>

- Enhancement in the sensitivity is not simply due to the events with low hadron energy
- The normalized $\Delta \chi^2$ per event is slightly higher for larger hadron energy bins
50 kt ICAL can rule out the wrong hierarchy with $\Delta \chi^2 \approx 9.5$ in 10 years.
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.
MH Discovery with ICAL+T2K+NOvA

3σ median sensitivity can be achieved in 6 years

Thakore, Agarwalla, work in progress
Significant improvement in the precision measurement of atmospheric mass splitting by adding hadron energy information with muon momentum

ICAL’s expected precision on atmospheric mass splitting is better than SK

Octant of $\theta_{23}$ with ICAL-INO

Median $2\sigma$ discovery of $\theta_{23}$ octant is possible if $\theta_{23}$ is sufficiently away from maximal value


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Non-Standard Oscillation Physics
Active-Sterile Mixing at ICAL-INo

$\mu^-$ Event Distributions

$\Delta m^2_{41} = 10^{-2} \text{eV}^2$

$\theta_{14} = \theta_{34} = 0$

<table>
<thead>
<tr>
<th>Case</th>
<th>$# \mu^-$</th>
<th>$# \mu^+$</th>
</tr>
</thead>
<tbody>
<tr>
<td>4f Matter Oscillations</td>
<td>4295.59</td>
<td>1877.41</td>
</tr>
<tr>
<td>3f Matter Oscillations</td>
<td>4736.1</td>
<td>2070.05</td>
</tr>
</tbody>
</table>

Preliminary

Thakore, Devi, Agarwalla, Dighe, in preparation (INO Collaboration)
CC Analysis
500 kt.yr exposure
Preliminary

Thakore, Devi, Agarwalla, Dighe, in preparation (INO Collaboration)
NC Analysis to Probe Active-Sterile Oscillation

\[ |P_h| = \sum_i |p_i|, \text{ where } i \text{ is the total hadrons in the final state} \]

Preliminary

averaged over all \( \cos \theta_{\text{had}} \)

Thakore, Devi, Agarwalla, Dighe, in preparation (INO Collaboration)
Preliminary averaged over all $\cos\theta_{\text{had}}$

\[
\begin{align*}
\chi^2 / \text{ndf} & \quad 16.61 / 27 \\
a & \quad 0.6126 \pm 0.009635 \\
b & \quad 0.3344 \pm 0.00362
\end{align*}
\]
NC Shower Event Distribution

Thakore, Devi, Agarwalla, Dighe, in preparation (INO Collaboration)

Preliminary

500 kt.yr exposure

$\Delta m^2_{41} = 10 \text{ eV}^2$
Exclusion Plot from NC Analysis

Matter Oscillations
- 90% C.L.
- 68% C.L.

Preliminary

Thakore, Devi, Agarwalla, Dighe, in preparation (INO Collaboration)
Spectral Study is must for NSI’S. Nothing can be done with only rates

Khatun, Chatterjee, Thakore, Agarwalla, in preparation (INO Collaboration)
Constraints on NSI’s

Khatun, Chatterjee, Thakore, Agarwalla, in preparation (INO Collaboration)

See also, Choubey, Ghosh, Ohlsson, Tiwari, arXiv: 1507.02211 [hep-ph]
How quickly can we constrain these NSI’s?

Khatun, Chatterjee, Thakore, Agarwalla, in preparation (INO Collaboration)

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## How Robust is MH Study with NSI’s?

### Preliminary

<table>
<thead>
<tr>
<th>True MO</th>
<th>Analysis Mode</th>
<th>SM</th>
<th>With NSI</th>
<th>Reduce</th>
</tr>
</thead>
<tbody>
<tr>
<td>LE</td>
<td>(E_{\mu}, \cos \theta_{\mu})</td>
<td>5.62</td>
<td>4.81</td>
<td>14.4%</td>
</tr>
<tr>
<td></td>
<td>(E_{\mu}'<em>{had}, E</em>{\mu}, \cos \theta_{\mu})</td>
<td>8.66</td>
<td>7.49</td>
<td>13.5%</td>
</tr>
<tr>
<td>NH</td>
<td>(E_{\mu}, \cos \theta_{\mu})</td>
<td>5.31</td>
<td>4.14</td>
<td>22.0%</td>
</tr>
<tr>
<td></td>
<td>(E_{\mu}'<em>{had}, E</em>{\mu}, \cos \theta_{\mu})</td>
<td>8.48</td>
<td>6.88</td>
<td>18.8%</td>
</tr>
<tr>
<td>IH</td>
<td>(E_{\mu}, \cos \theta_{\mu})</td>
<td>5.96</td>
<td>5.37</td>
<td>9.9%</td>
</tr>
<tr>
<td></td>
<td>(E_{\mu}'<em>{had}, E</em>{\mu}, \cos \theta_{\mu})</td>
<td>9.13</td>
<td>8.16</td>
<td>10.6%</td>
</tr>
<tr>
<td>HE</td>
<td>(E_{\mu}, \cos \theta_{\mu})</td>
<td>5.66</td>
<td>4.95</td>
<td>12.5%</td>
</tr>
<tr>
<td></td>
<td>(E_{\mu}'<em>{had}, E</em>{\mu}, \cos \theta_{\mu})</td>
<td>8.99</td>
<td>7.66</td>
<td>14.8%</td>
</tr>
</tbody>
</table>

One extra parameter in the fit: $\varepsilon_{\mu\tau}$ in the range ± 10%
One extra parameter in the fit: $\epsilon_{\mu\tau}$ in the range $\pm 10\%$

Preliminary
Current Status of INO

Pre-project activities started with an initial grant of ~ 15 M$

- 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 1/8\textsuperscript{th} size 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

- Full project approved by PM’s cabinet committee to start construction
Glimpse of Activities at the IICHEP Site

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Glimpse of Activities at the INO Site

- survey work
- receiving sump with 12 lakhs litre capacity
- fencing work
• INO Graduate Training Program started in August 2008, students are affiliated to HBNI

• At present students being trained for 1 year at TIFR in both experimental techniques & theory

• After completion of coursework, attached to Ph.D. guides at various collaborating institutions

• Many short/long term visits to RPC labs (Mumbai & Kolkata) of students & faculties from Universities in last several years

• Several students from 1st batch (2008) and 2nd batch (2009) are already working as post-docs at different places

• 7th batch of 6 students have started their course work at TIFR in 2014
Final Remarks

Stay Tuned!

More Analyses and Results are going to come soon

Comments and Suggestions are most welcome

Just drop an email to our Physics Coordinators

(amol@theory.tifr.res.in or sruba@prl.res.in)

A Request: INO Students are extremely hard working and motivated!

Hire them as Post-docs

Thank you!

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The Vavilov probability density function in the standard form is defined by:

\[ P(x; \kappa, \beta^2) = \frac{1}{2\pi i} \int_{c-i\infty}^{c+i\infty} \phi(s)e^{xs}ds, \quad \text{(C.1)} \]

where

\[ \phi(s) = e^C e^{\psi(s)}, \quad C = \kappa(1 + \beta^2\gamma), \quad \text{(C.2)} \]

and

\[ \psi(s) = s \ln \kappa + (s + \beta^2\kappa) \cdot \left[ \int_0^1 \frac{1 - e^{-st/\kappa}}{t} dt - \gamma \right] - \kappa e^{-s/\kappa}, \quad \text{(C.3)} \]

where \( \gamma = 0.577 \ldots \) is Euler's constant.

The parameters mean and variance \( (\sigma^2) \) of the distribution in Eq. (C.1) are given by

\[ \text{mean} = \gamma - 1 - \ln \kappa - \beta^2; \quad \sigma^2 = \frac{2 - \beta^2}{2\kappa}. \quad \text{(C.4)} \]

For \( \kappa \leq 0.05 \), the Vavilov distribution may be approximated by the Landau distribution, while for \( \kappa \geq 10 \), it may be approximated by the Gaussian approximation, with the corresponding mean and variance.

We have used the Vavilov distribution function \( P(x; \kappa, \beta^2) \) defined above, which is also built into ROOT, as the basic distribution for the fit. However the hadron hit distribution itself is fitted to the modified distribution \((P_4/P_3) \ P((x - P_2)/P_3; \ P_0, \ P_1)\), to account for the x-scaling \( (P_3) \), normalization \( P_4 \) and the shift of the peak to a non-zero value, \( P_2 \). Clearly \( P_0 = \kappa \) and \( P_1 = \beta^2 \). The modified mean and variance are then

\[ \text{Mean}_{Vavilov} = (\gamma - 1 - \ln P_0 - P_1) \ P_3 + P_2, \quad \sigma^2_{Vavilov} = \frac{(2 - P_1) P_2^2}{2P_0}. \quad \text{(C.5)} \]

These are the quantities used while presenting the energy response of hadrons in the ICAL detector.
Three Flavor Effects in $\nu_\mu \rightarrow \nu_e$ oscillation probability

The appearance probability $(\nu_\mu \rightarrow \nu_e)$ in matter, up to second order in the small parameters $\alpha \equiv \Delta m^2_{21}/\Delta m^2_{31}$ and $\sin 2\theta_{13}$, is given by:

$$P_{\mu e} \simeq \frac{\sin^2 2\theta_{13}}{(1 - \hat{A})^2} \frac{\sin^2 [(1 - \hat{A})\Delta]}{1 - \hat{A}} \sin^2 \theta_{23} + \alpha \sin 2\theta_{13} \xi \sin \delta_{CP} \sin(\Delta) \frac{\sin(\hat{A}\Delta)}{\hat{A}} \frac{\sin[(1 - \hat{A})\Delta]}{1 - \hat{A}} \cos \delta_{CP} \cos(\Delta) + \alpha^2 \cos^2 \theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(\hat{A}\Delta)}{\hat{A}^2};$$

where $\Delta \equiv \Delta m^2_{31} L/(4E)$, $\xi \equiv \cos \theta_{13} \sin 2\theta_{21} \sin 2\theta_{23}$, and $\hat{A} \equiv \pm (2\sqrt{2}G_F n_e E) / \Delta m^2_{31}$.

Changes sign with $\text{sgn}(\Delta m^2_{31})$; key to resolve hierarchy!

Changes sign with polarity; causes fake CP asymmetry!

Resolves octant

$\theta_{13}$ Driven

CP odd

CP even

Solar Term

Cervera et al., hep-ph/0002108
Freund et al., hep-ph/0105071
See also, Agarwalla et al., arXiv:1302.6773 [hep-ph]

This channel suffers from: (Hierarchy – $\delta_{CP}$) & (Octant – $\delta_{CP}$) degeneracy! How can we break them?
Information on $\theta_{23}$ comes from: a) atmospheric neutrinos and b) accelerator neutrinos

In two-flavor scenario: $P_{\mu\mu} = 1 - \sin^2 2\theta_{\text{eff}} \sin^2 \left(\frac{\Delta m^2_{\text{eff}} L}{4E}\right)$

For accelerator neutrinos: relate effective 2-flavor parameters with 3-flavor parameters:

$$\Delta m^2_{\text{eff}} = \Delta m^2_{31} - \Delta m^2_{21} (\cos^2 \theta_{12} - \cos \delta_{\text{CP}} \sin \theta_{13} \sin 2\theta_{12} \tan \theta_{23})$$

where $\frac{|U_{\mu 3}|^2}{|U_{\tau 3}|^2} = \tan^2 \theta_{23}$


Combining beam and atmospheric data in MINOS, we have:


$$\sin^2 2\theta_{\text{eff}} = 0.95^{+0.035}_{-0.036} \times 10^{21} \text{ p.o.t}$$

$$\sin^2 2\bar{\theta}_{\text{eff}} = 0.97^{+0.03}_{-0.08} \times 3.36 \times 10^{21} \text{ p.o.t}$$

Atmospheric data, dominated by Super-Kamiokande, still prefers maximal value of $\sin^2 2\theta_{\text{eff}} = 1$ ($\geq 0.94$ (90% C.L.))

Talk by Y. Itow in Neutrino 2012 conference, Kyoto, Japan

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Bounds on $\theta_{23}$ from the global fits

In $\nu_\mu$ survival probability, the dominant term mainly sensitive to $\sin^22\theta_{23}$

If $\sin^22\theta_{23}$ differs from 1 (as indicated by recent data), we get two solutions for $\theta_{23}$:

one in lower octant (LO: $\theta_{23} < 45$ degree), other in higher octant (HO: $\theta_{23} > 45$ degree)

In other words, if $(0.5 - \sin^2\theta_{23})$ is +ve (-ve) then $\theta_{23}$ belongs to LO (HO)

This is known as the octant ambiguity of $\theta_{23}$

Fogli and Lisi, hep-ph/9604415

<table>
<thead>
<tr>
<th>Conferences</th>
<th>After Neutrino 2012</th>
<th>After NuTeV 2013</th>
<th>After TAUP 2013</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sin^2\theta_{23}$</td>
<td>$0.41^{+0.037}<em>{-0.025} \oplus 0.59^{+0.021}</em>{-0.022}$</td>
<td>$0.437^{+0.061}_{-0.031}$</td>
<td>$0.446^{+0.007}<em>{-0.007} \oplus 0.587^{+0.032}</em>{-0.037}$</td>
</tr>
<tr>
<td>$3\sigma$ range</td>
<td>$0.34 \rightarrow 0.67$</td>
<td>$0.357 \rightarrow 0.654$</td>
<td>$0.366 \rightarrow 0.663$</td>
</tr>
<tr>
<td>$1\sigma$ precision (relative)</td>
<td>13.4%</td>
<td>11.3%</td>
<td>11.1%</td>
</tr>
</tbody>
</table>

Based on Gonzalez-Garcia, Maltoni, Salvado, Schwetz, http://www.nu-fit.org

Global fit disfavors maximal 2-3 mixing at $1.4\sigma$ confidence level (mostly driven by MINOS)

$\nu_\mu$ to $\nu_e$ oscillation data can break this degeneracy

The preferred value would depend on the choice of the neutrino mass hierarchy

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New Measurements of Atmospheric Parameters

Already mixing angle is better constrained by T2K in comparison to SK and MINOS

<table>
<thead>
<tr>
<th></th>
<th>Best-fit ± FC 68% CL</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(Δm^2 units 10^{-3} eV^2/c^4)</td>
</tr>
<tr>
<td>NH</td>
<td>sin^2θ_{23}</td>
</tr>
<tr>
<td></td>
<td>Δm^2_{32}</td>
</tr>
<tr>
<td>IH</td>
<td>sin^2θ_{23}</td>
</tr>
<tr>
<td></td>
<td>Δm^2_{13}</td>
</tr>
</tbody>
</table>

Talk by C. Walter in Neutrino 2014

S. K. Agarwalla, MITP, Johannes Gutenberg University, Mainz, Germany, 28th July, 2015
Present Status of Neutrino Oscillation Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$bfp \pm 1\sigma$</th>
<th>$3\sigma$ range</th>
<th>Relative 1σ Precision</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sin^2 \theta_{12}$</td>
<td>$0.304^{+0.012}_{-0.012}$</td>
<td>$0.270 \rightarrow 0.344$</td>
<td>4%</td>
</tr>
<tr>
<td>$\theta_{12}/^\circ$</td>
<td>$33.48^{+0.77}_{-0.74}$</td>
<td>$31.30 \rightarrow 35.90$</td>
<td>9.6%</td>
</tr>
<tr>
<td>$\sin^2 \theta_{23}$</td>
<td>$[0.451^{+0.001}<em>{-0.001}] \oplus 0.577^{+0.027}</em>{-0.035}$</td>
<td>$0.385 \rightarrow 0.644$</td>
<td>4.8%</td>
</tr>
<tr>
<td>$\theta_{23}/^\circ$</td>
<td>$[42.2^{+0.1}<em>{-0.1}] \oplus 49.4^{+1.6}</em>{-2.0}$</td>
<td>$38.4 \rightarrow 53.3$</td>
<td>(Not Known)</td>
</tr>
<tr>
<td>$\sin^2 \theta_{13}$</td>
<td>$0.0219^{+0.0010}_{-0.0011}$</td>
<td>$0.0188 \rightarrow 0.0251$</td>
<td>2.4%</td>
</tr>
<tr>
<td>$\theta_{13}/^\circ$</td>
<td>$8.52^{+0.20}_{-0.21}$</td>
<td>$7.87 \rightarrow 9.11$</td>
<td></td>
</tr>
<tr>
<td>$\delta_{CP}/^\circ$</td>
<td>$251^{+67}_{-59}$</td>
<td>$0 \rightarrow 360$</td>
<td></td>
</tr>
<tr>
<td>$\Delta m_{21}^2/10^{-5}$ eV$^2$</td>
<td>$7.50^{+0.19}_{-0.17}$</td>
<td>$7.03 \rightarrow 8.09$</td>
<td></td>
</tr>
<tr>
<td>$\Delta m_{31}^2/10^{-3}$ eV$^2$</td>
<td>$[+2.458^{+0.002}_{-0.002}]$</td>
<td>$+2.325 \rightarrow +2.599$</td>
<td></td>
</tr>
<tr>
<td>$\Delta m_{32}^2/10^{-3}$ eV$^2$</td>
<td>$-2.448^{+0.047}_{-0.047}$</td>
<td>$-2.590 \rightarrow -2.307$</td>
<td></td>
</tr>
</tbody>
</table>

Based on the data available after Neutrino 2014 conference


S. K. Agarwalla, MITP, Johannes Gutenberg University, Mainz, Germany, 28th July, 2015
**1. What is the hierarchy of the neutrino mass spectrum, normal or inverted?**

- The sign of $\Delta m_{31}^2 = m_3^2 - m_1^2$ is not known!
- Currently do not know which neutrino is the heaviest?
- Only have a lower bound on the mass of the heaviest $\nu$!

\[ \sqrt{2.5 \cdot 10^{-3}}eV^2 \sim 0.05\ eV \]

**2. What is the octant of the 2-3 mixing angle, lower ($\theta_{23} < 45^\circ$) or higher ($\theta_{23} > 45^\circ$)?**

Measure $\theta_{23}$ precisely, Establish deviation from maximality at higher C.L. Then look for Octant

**2. Is there CP violation in the leptonic sector, as in the quark sector?**

Mixing can cause CP violation in the leptonic sector (if $\delta_{CP}$ differs from $0^\circ$ and $180^\circ$)

Need to measure the CP-odd asymmetries: $\Delta P_{\alpha\beta} \equiv P(\nu_\alpha \rightarrow \nu_\beta; L) - P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta; L)$ ($\alpha \neq \beta$)

With current knowledge of $\theta_{13}$, resolving these unknowns fall within our reach

Sub-leading 3 flavor effects are extremely crucial in current & future oscillation expts

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S. K. Agarwalla, MITP, Johannes Gutenberg University, Mainz, Germany, 28th July, 2015
Introducing INO Collaboration

Ahmadabad: Physical Research Laboratory
Aligarh: Aligarh Muslim University
Allahabad: HRI
Bhubaneswar: IoP, Utkal University
Calicut: University of Calicut
Chandigarh: Panjab University
Chennai: IIT-Madras, IMSc
Delhi: University of Delhi
Kalpakkam: IGCAR
Kolkata: SINC, VECC, University of Calcutta
Lucknow: Lucknow University
Madurai: American College
Mumbai: BARC, IIT-Bombay, TIFR, CMEMS
Mysore: University of Mysore
Srinagar: University of Kashmir
Varanasi: Banaras Hindu University

Nearly 100 scientists from 23 research institutes & universities all over India

One of the largest basic science projects in India in terms of man power & cost as well

We are growing day by day
International Collaborators are most welcome

S. K. Agarwalla, MITP, Johannes Gutenberg University, Mainz, Germany, 28th July, 2015
A multi-institutional attempt to build a world-class underground facility to study fundamental issues in science with special emphasis on neutrinos

With ~1 km all-round rock cover accessed through a 2 km long tunnel. A large and several smaller caverns to pursue many experimental programs

Complementary to ongoing efforts worldwide to explore neutrino properties

A mega-science project (~250 M$) in India, jointly funded (50:50) by the Department of Atomic Energy and the Department of Science and Technology

International Community is welcome to participate in ICAL@INO activity. INO facility is also available to the entire community for setting up experiments like Neutrino-less Double Beta Decay, Direct Dark Matter searches
Coordinates of INO

Bodi West Hills
Pottipuram Village
9°58’ N and 77°16’ E

Located 115 km west of the Madurai city in the Theni district of Tamil Nadu

Madurai has an International Airport

S. K. Agarwalla, MITP, Johannes Gutenberg University, Mainz, Germany, 28th July, 2015
Approved projects under INO

• Come up with an underground lab & surface facilities near Pottipuram village in Theni district of Tamil Nadu

• Build massive 50 kt magnetized Iron calorimeter (ICAL) detector to study properties of neutrinos

• Construction of INO centre at Madurai: Inter-Institutional Centre for High Energy Physics (IICHEP)

• Human Resource Development (INO Graduate Training Program)

• Completely in-house Detector R&D with substantial INO-Industry interface

• Time Frame for 1st module: 2019

S. K. Agarwalla, MITP, Johannes Gutenberg University, Mainz, Germany, 28th July, 2015
Study Atmospheric neutrinos w/ a wide range of Baselines & Energies

Recent discovery of large $\theta_{13}$: A good news for ICAL-INO

What do we want to achieve?

- Reconfirm neutrino oscillations using neutrinos and anti-neutrinos separately
- Improved precision of atmospheric oscillation parameters
- Determine neutrino mass hierarchy using matter effects via charge discrimination
- Measure the deviation of 2-3 mixing angle from its maximal value and its octant
- Test bed for various new physics like NSI, CPT violation, long range forces
- Detect Ultra High Energy Neutrinos, Cosmic Muons, Indirect searches of DM