Physics with India-based Neutrino Observatory (INO)

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All documents regarding INO are available at
http://www.imsc.res.in/~ino

ICHEP 06, Moscow, July 2006
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May also host some smaller experiments (such as neutrinoless double beta decay searches) which require low cosmic ray background environments.
Location of PUSHEP
A view of PUSHEP

PUSHEP in the Nilagiris, near Ooty (Masinagudi)
Underground Cavern

Layout of the Underground Cavern

Size of the experimental hall
150 m X 22 m X 30 m
Magnetized Iron Calorimeter: ICAL

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- Similar to the earlier Monolith proposal.
INO Detector Concept
Two possible magnet designs
Resistive Plate Chamber: RPC

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- The $z$ coordinate is provided by the location of RPC itself.
- Good reconstruction of energy and direction of charged particles.
Total number of RPC units: 27000
Number of electronic readout channels: 3.6 million
Physics Motivations

- Reconfirm the first oscillation dip as a function of $L/E$ in atmospheric neutrinos (to a greater significance level)
- Measure $|\Delta_{31}|$ and $\sin^2 2\theta_{23}$ precisely
- Determine neutrino mass hierarchy (normal/inverted)
- Resolve the $\theta_{23}$ octant ambiguity
- Distinguish between $\nu_\mu \leftrightarrow \nu_\tau$ and $\nu_\mu \leftrightarrow \nu_s$
- Search for CPT violation
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All results are generated assuming 15% resolution in $L$ as well as $E$, unless specified otherwise.
$L/E$ distribution of muon events

$\Delta m^2 = 2 \times 10^{-3}$ eV$^2$

$\Delta m^2 = 3 \times 10^{-3}$ eV$^2$

red: down-going, blue: up-going

Exposure 250 kt-years, $\theta_{23} = \pi/4$, $E_\mu > 5$ GeV
Up/Down ratio of muon events

Position of the dip $\Rightarrow \Delta m^2_{\text{atm}}$

Up/Down ratio at the dip $\Rightarrow \sin^2 2\theta_{23}$
### Precision for $|\Delta_{31}|$ and $\sin^2 \theta_{23}$

<table>
<thead>
<tr>
<th>Experiment</th>
<th>$\Delta_{31}$</th>
<th>$\sin^2 \theta_{23}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current data</td>
<td>88%</td>
<td>79%</td>
</tr>
<tr>
<td>MINOS + CNGS</td>
<td>26%</td>
<td>78%</td>
</tr>
<tr>
<td>T2K (SK, 0.75 MW, 5 years)</td>
<td>12%</td>
<td>46%</td>
</tr>
<tr>
<td>NO$\nu$A (30 Kton, 0.6 MW, 5 years)</td>
<td>25%</td>
<td>86%</td>
</tr>
<tr>
<td>ICAL (50 Kton, atm $\nu$, 5 years)</td>
<td>20%</td>
<td>60%</td>
</tr>
</tbody>
</table>

- **Input values:** $|\Delta_{31}| = 0.002 \text{ eV}^2$ and $\theta_{23} = \pi/4$.
- **Table adapted from P. Huber et al., hep-ph/0412133,** with the information of ICAL added.
The relative error on $|\Delta_{31}|$ and $\sin^2 \theta_{23}$

**Error as a function of the input value of $|\Delta_{31}|$ at 2 $\sigma$.**
Mass hierarchy (normal/inverted)

- At resonance energies and long pathlengths, matter effects modify $\nu_\mu$ survival probability significantly.

  R. Gandhi et al., PRL 94, 051801 (2005)
  PRD 73, 053001 (2006)

- Situation reversed for antineutrinos
Up-down ratios for $\nu$ and $\bar{\nu}$

The difference in the up/down ratio for $\nu_\mu$ and $\bar{\nu}_\mu$:
$A \equiv U/D - \bar{U}/\bar{D}$ as a function of $L/E$

is very sensitive to the sign of $\Delta_{31}$.

R: energy/time resolution included

blue: normal hierarchy
red: inverted hierarchy

D. Indumathi and M.V.N. Murthy,
PRD 71, 013001 (2005)
INO Project Report,
May 2006

Higher $E_{\text{min}}$ $\Rightarrow$ more asymmetry but less events
\[ \Delta A \equiv A_{\text{norm}} - A_{\text{inv}} \]

<table>
<thead>
<tr>
<th>Exposure (kt-years)</th>
<th>( \theta_{13} )</th>
<th>( \Delta A )</th>
<th>Significance</th>
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<tbody>
<tr>
<td>480</td>
<td>7°</td>
<td>0.167 ± 0.230</td>
<td>0.7( \sigma ), 51.6%</td>
</tr>
<tr>
<td>1120</td>
<td>7°</td>
<td>0.167 ± 0.151</td>
<td>1.1( \sigma ), 72.9%</td>
</tr>
<tr>
<td>480</td>
<td>11°</td>
<td>0.415 ± 0.230</td>
<td>1.8( \sigma ), 92.8%</td>
</tr>
<tr>
<td>1120</td>
<td>11°</td>
<td>0.415 ± 0.150</td>
<td>2.8( \sigma ), 99.6%</td>
</tr>
<tr>
<td>480</td>
<td>7°</td>
<td>0.232 ± 0.220</td>
<td>1.1( \sigma ), 72.9%</td>
</tr>
<tr>
<td>1120</td>
<td>7°</td>
<td>0.232 ± 0.144</td>
<td>1.6( \sigma ), 89.0%</td>
</tr>
<tr>
<td>480</td>
<td>11°</td>
<td>0.565 ± 0.220</td>
<td>2.6( \sigma ), 99.1%</td>
</tr>
<tr>
<td>1120</td>
<td>11°</td>
<td>0.565 ± 0.144</td>
<td>3.9( \sigma ), 99.99%</td>
</tr>
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- \( E \) and \( L \) resolutions of 15\% (upper) and 10\% (lower).
- Exposure time 480 kt-year \( \longrightarrow \) 1120 kt-year has the same effect as resolution 15\% \( \longrightarrow \) 10\%.
- Importance of \( L \) and \( E \) resolution highlighted in S. Petcov and T. Schwetz, NPB 740, 1 (2006).
Octant ambiguity of $\theta_{23}$

(Is $\theta_{23}$ greater or less than $\pi/4$ ?)

- One of the matter dependent terms in $P_{\mu\mu}$ goes as $\sin^4 \theta_{23}$. By appropriate cuts on $E$ and $L$ this term can be isolated and to determine if $\theta_{23}$ is greater or less than $\pi/4$.

  D. Indumathi et al., hep-ph/0603032

- At present $|D \equiv 0.5 - \sin^2 \theta_{23}|$ is constrained to be about 0.16 at $3\sigma$. If $\sin^2 \theta_{13} = 0.02$ then 1000 kt-year exposure can:
  - measure a non-zero value for $|D| > 0.09$ at $3\sigma$.
  - Determine the sign of $D$ for $|D| > 0.1$ at $3\sigma$.
$P_{\mu\mu}$ as a function of $\theta_{23}$

For intermediate $E$, even the sign of $D$ discernible
Distinguishing $\nu_\mu \leftrightarrow \nu_\tau$ from $\nu_\mu \leftrightarrow \nu_s$

Muonless events are produced by DIS neutral current (NC) interactions of all active neutrino flavours.
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- $\nu_\tau$ CC events (above 4 GeV) produce a $\tau$, whose decays are muonless 80% of the time.

D. Choudhury and A. Datta, hep-ph/0606100

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- Possible to determine directly (rather than by global fits) what fraction of $\nu_\mu$ are oscillating into sterile neutrinos.

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Up-down asymmetry for muonless events

Asymmetry vs. $E$ for different $\Delta_{31}$ values for $\nu_\mu \rightarrow \nu_\tau$ and $\nu_\mu \rightarrow \nu_s$

$\sin^2 2\theta = 1.$
CPT violation

- Charge determination $\Rightarrow$
  both $P_{\mu\mu}$ and $P_{\bar{\mu}\bar{\mu}}$ measurable independently.
- Possibility of searching for CPT violation.
- CPT violation Parametrized as: $\mathcal{L}_{\text{CPT}} = \bar{\nu}_L^\alpha b_\alpha^\mu \gamma_\mu \nu_L^\beta$
  V. Barger et al., PRL 85, 5055 (2000)
- Energy operator becomes $H = m^2/2E + b^0$
- Measurable CPT violating parameter: $\delta b$, the difference in the eigenvalues of the $b^0$ matrix
Sensitivity to CPT violation

$L/E$ distribution can detect $\delta b \gtrsim 10^{-23}$ GeV

To be compared to $\Delta m^2/2E \sim 10^{-21}$ GeV
Determination of $\delta b$

For $\delta b > 10^{-22}$ GeV, distribution in $L$ is sensitive to the value of $\delta b$.
Concluding Remarks

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- We welcome more International participation.
That’s all, folks!

http://www.imsc.res.in/~ino
\( P_{\mu\mu} \) in vacuum and matter

Muon neutrino survival probability in vacuum:

\[
P_{\mu\mu}(\text{vac}) = 1 - \sin^2 2\theta_{23} \cos^2 \theta_{13} \sin^2 (1.27 \Delta_{31} L/E) - \sin^4 \theta_{23} \sin^2 2\theta_{13} \sin^2 (1.27 \Delta_{31} L/E)
\]

Muon neutrino survival probability in matter:

\[
P_{\mu\mu}(\text{mat}) = 1 - \sin^2 2\theta_{23} \cos^2 \theta_{13}^m \sin^2 [1.27(\Delta_{31} + A + \Delta_{31}^m)L/2E] - \sin^2 2\theta_{23} \sin^2 \theta_{13}^m \sin^2 [1.27(\Delta_{31} + A - \Delta_{31}^m)L/2E] - \sin^4 \theta_{23} \sin^2 2\theta_{13}^m \sin^2 (1.27\Delta_{31}^m L/E)
\]

\[
A = 2\sqrt{2}G_F N_e E
\]
\( P_{\mu\mu} \) for both hierarchies, \( L = 9700 \text{ km} \)

\[
\begin{align*}
E (\text{GeV}) & \quad P_{\mu\mu} \\
2 & \quad \Delta_{31} > 0 \\
4 & \quad \text{vacuum} \\
6 & \quad \Delta_{31} < 0 \\
8 & \\
10 & \\
12 & \\
14 & \\
16 & \\
18 & \\
20 & \\
\end{align*}
\]
$P_{\mu\mu}$ vs. $\theta_{23}$ for $L = 9700$ km
If we parametrize CPT violation as
\[ \Delta = \Delta_{\text{GUT}} + \Delta_{\text{CPT}} \text{ and } \bar{\Delta} = \Delta_{\text{GUT}} - \Delta_{\text{CPT}}, \]
INO is sensitive to \[ \frac{\Delta_{\text{CPT}}}{\Delta_{\text{GUT}}} \sim 1\% \]