Physics with India-based Neutrino Observatory (INO)

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

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India-based Neutrino Observatory: INO

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- May also host some smaller experiments (such as neutrinoless double beta decay searches) which require low cosmic ray background environments.
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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- Magnetic field (1.3 T) allows determination of muon charge so that $\nu_\mu$ and $\bar{\nu}_\mu$ can be studied separately.
- Similar to the earlier Monolith proposal.
INO Detector Concept

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Two possible magnet designs
Resistive Plate Chamber: RPC

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- Pickout strips, 3 cm wide, above and below each RPC for the determination of $x$ and $y$ coordinates of the passage of charged particle.
- The $z$ coordinate is provided by the location of RPC itself.
- Good reconstruction of energy and direction of charged particles.
**Construction of RPC**

- *Two 2 mm thick float Glass Separated by 2 mm spacer*
- *Pickup strips*
- *Glass plates*
- *Resistive coating on the outer surfaces of glass*

- **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$^2$

Up, Down events/bin

$log_{10}(L/E \ (\text{km/GeV}))$

red: down-going, blue: up-going

Exposure 250 kt-years, $\theta_{23} = \pi/4$, $E_{\text{thresh}} = 5$ 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: $|\Delta_{31}| = 0.002$ 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 $\sin^2 \theta_{23}$

**$\Delta m_{31}^2$-precision**

**$\sin^2 \theta_{23}$-precision**

Error as a function of the input value of $|\Delta_{31}|$ at 2 $\sigma$. 

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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 Interim 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>
</tr>
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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>
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<td>1120</td>
<td>11°</td>
<td>0.565 ± 0.144</td>
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- \( E \) and \( L \) resolutions of 15\% (upper) and 10\% (lower).
- Exposure time 480 kt-year \(\rightarrow\) 1120 kt-year
  has the same effect as resolution 15\% \(\rightarrow\) 10\%.
- Importance of \( L \) and \( E \) resolution highlighted in
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 high $E$, only the magnitude of $D$ measurable
- For intermediate $E$, even the sign of $D$ discernible
Distinguishing $\nu_\mu \leftrightarrow \nu_\tau$ from $\nu_\mu \leftrightarrow \nu_s$

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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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- MINOS is also capable of doing this.
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: $\mathcal{L}_{\text{CPT}} = \bar{\nu}_{\mu}^{\alpha} b_{\alpha\beta}^{\mu} \gamma_{\mu} \nu_{L}^{\beta}$
  
  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

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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!
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, $L = 9700$ km
$P_{\mu\mu}$ vs. $\theta_{23}$ for $L = 9700$ km
CPT violation: a comment

If we parametrize CPT violation as
\[ \Delta = \Delta_{\text{GUT}} + \Delta_{\text{CPT}} \] and \[ \overline{\Delta} = \Delta_{\text{GUT}} - \Delta_{\text{CPT}}, \]
INO is sensitive to \[ \Delta_{\text{CPT}}/\Delta_{\text{GUT}} \sim 1\% \]