Future Atmospheric Neutrino Experiments

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Tata Institute, Mumbai
Need for new Atmospheric Neutrino Detectors

• Experimental field of Neutrino Physics has moved to the phase of decisive and precision measurement of oscillation parameters.

• New and planned long base line experiments will provide bulk of the data necessary to achieve this.

• Is there still need for new atmospheric neutrino experiments?
Physics with Atmospheric Neutrinos

- It span a large range of $L/E$.
- Oscillation can be seen as a function of $L/E$.
- Possibility of observing matter effect.
- Sensitivity to the sign of $\Delta m^2_{23}$.
- Measuring $\theta_{13}$.
- CP Phase measurement.
Magnetised Iron Tracking Calorimeter
India-based Neutrino Observatory (INO) initiative

Goal: A large mass detector with charge identification capability

- Two phase approach:

<table>
<thead>
<tr>
<th>R &amp; D and Construction</th>
<th>Operation of the Detector</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Phase I</strong></td>
<td><strong>Phase I</strong></td>
</tr>
<tr>
<td>Physics studies,</td>
<td>Physics with Atmospheric</td>
</tr>
<tr>
<td>Detector R &amp; D,</td>
<td>Neutrinos</td>
</tr>
<tr>
<td>Site survey,</td>
<td><strong>Phase II</strong></td>
</tr>
<tr>
<td>Human resource</td>
<td>Physics with Neutrino</td>
</tr>
<tr>
<td>development</td>
<td>beam from a factory</td>
</tr>
<tr>
<td><strong>Phase II</strong></td>
<td></td>
</tr>
<tr>
<td>Construction of the</td>
<td></td>
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<tr>
<td>detector</td>
<td></td>
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</table>
Choice of Neutrino Source and Detector

- **Neutrino Source**
  - Need to cover a large L/E range.
    - Large L range
    - Large $E_\nu$ range
  - Use Atmospheric neutrinos as source.

- **Detector Choice**
  - Should have large target mass (50-100 KT)
  - Good tracking and Energy resolution (tracking calorimeter)
  - Good directionality (<= 1 nsec time resolution)
  - Ease of construction
  - Modularity
  - Complimentarity with other existing and proposed detectors
  - Use magnetised iron as target mass and RPC as active detector medium.
INO Detector Concept
**Construction of RPC**

Two 2 mm thick float Glass
Separated by 2 mm spacer

- 2 mm thick spacer
- Pickup strips
- Glass plates
- Resistive coating on the outer surfaces of glass

*Neutrino 2006, Santa Fe, USA*
<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 12 m</td>
</tr>
<tr>
<td>Detector dimension</td>
<td>48 m X 16 m X 12 m</td>
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<tr>
<td>No. of layers</td>
<td>140</td>
</tr>
<tr>
<td>Iron plate thickness</td>
<td>6 cm</td>
</tr>
<tr>
<td>Gap for RPC trays</td>
<td>2.5 cm</td>
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<tr>
<td>Magnetic field</td>
<td>1.3 Tesla</td>
</tr>
<tr>
<td>RPC unit dimension</td>
<td>2 m X 2 m</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>27000</td>
</tr>
<tr>
<td>No of Electronic channels</td>
<td>$3.6 \times 10^6$</td>
</tr>
</tbody>
</table>
• **Built RPCs of different sizes**
  - 30 cm X 30 cm
  - 120 cm X 90 cm
RPC Efficiencies and Timing

**TIFR RPC Efficiency**

- Freon-134a 62%
- Freon-134a 57%
- Freon-134a 52%
- Freon-134a 46%

**Time Resolution**

- RPC
- Trigger scintillator

**RPC working in Streamer mode**

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Cosmic Muon Test

- Streamer mode (R134a=62%, Argon=30% and the rest Iso-Butane)
- Recording hits, timing, noise rates etc
Location of the Underground Laboratory

• Studies were performed on two potential sites.
  – Pykara Ultimate Stage Hydro Electric Project (PUSHEP) at Masinagudi, Tamilnadu
  – Rammam Hydro Electric Project Site at Darjeeling District in West Bengal

• INO Site Selection Committee after thorough evaluation have now recommended PUSHEP at Tamilnadu as the preferred site for the underground lab.
**Underground Cavern**

- **Layout of the Underground Cavern**
- **Size of the experimental hall**
  - 150 m X 22 m X 30 m

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**Experimental Hall**

**Access tunnel**

**Parking & Storage**

**Experimental Hall**

**Electronics**

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Physics using atmospheric neutrinos during Phase I

- Improved measurement of oscillation parameters.
- Search for potential matter effect in neutrino oscillation.
- Determining the sign of $\Delta m^2_{23}$ using matter effect.
- Is $\theta_{23}$ maximal? If not $\theta_{23} < \pi/4$ or $> \pi/4$?
- Probing CPT violation in neutrino sector.
- Ultra high energy muons in cosmic rays.
Physics with Neutrino beam from NUFACT – Phase II

- Determination of $\theta_{13}$.
- Determining the sign of $\Delta m^2_{23}$.
- Matter effect in $\nu_\mu \rightarrow \nu_\tau$ oscillation.
- Probing CP violation in leptonic sector.
The disappearance probability can be measured with a single detector and two equal sources:

\[ \frac{N_{\text{up}}(L/E)}{N_{\text{down}}(L'/E)} = P(\nu_\mu \rightarrow \nu_\mu; L/E) \]

\[ = 1 - \sin^2 (2\Theta) \sin^2 (1.27 \Delta m^2 L/E) \]
Precision Measurement of Oscillation Parameters
Matter Effect

Total no. of $\nu_\mu$ charge current events:

$$N_\mu = N_n \times M_\gamma \int dE \int d \cos \theta_z \left[ \frac{d^2 \phi_\mu}{dEd \cos \theta_z} P_{\mu\mu}(E, L) + \frac{d^2 \phi_e}{dEd \cos \theta_z} P_{e\mu}(E, L) \right] \sigma_\mu(E)$$

Neglecting $\Delta_{21}$

$$P^{vac}(\nu_\mu \rightarrow \nu_e) = \sin^2 \theta_{23} \sin^2 2\theta_{13} \sin^2 (1.27 \Delta_{31} L / E)$$

$$P^{mat}(\nu_\mu \rightarrow \nu_e) = \sin^2 \theta_{23} \sin^2 2\theta^m_{13} \sin^2 (1.27 \Delta^m_{31} L / E)$$

R. Gandhi et al PRL 94, 051801, 2005
Mass Hierarchy from matter induced asymmetry

Deviation from maximality of $\theta_{23}$
**CPT Violation**

The expression for survival probability for the case of CPTV 2-flavour oscillations

\[
P_{\mu \mu} (L) = 1 - \sin^2 2\theta \sin^2 \left( \frac{\delta_{32}}{4E} + \frac{\delta b}{2} \right) L \]

and

\[
\Delta P^{CPT}_{\mu \mu} = P_{\mu \mu} - P_{\mu \mu} = -\sin^2 2\theta \sin \left( \frac{\delta_{32}}{2E} L \right) \sin(\delta b L)
\]

Future water Cherenkov detectors
Hyper-Kamiokande

~1 Mton water Cherenkov detector at Kamioka

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Why this design has been chosen?

- Water depth < 50 m
  (If the present 20-inch PMT or similar one will be used.)
- Linear dimensions for light path < 100 m
- Optimization of $M_{FID}/M_{TOTAL}$
- Rock stability
  - Avoid sharp edges. Spherical shape is the best.
- solution: Tunnel-shaped cavity
- Single Cavity or Twin Cavities?
  - Single Cavity
    - $M_{FID}/M_{TOTAL}$ is better
    - Cost is lower
    - Larger area of stable rock mass needed.
  - Twin Cavities
    - Two detectors are independent. One detector is alive when the other is calibrated or maintained.
    - Both cavities should be excavated at the same time. But staging scenario is possible for the later phase of the detector construction.
- solution: Twin cavities
UNO Detector Conceptual Design

A Water Cherenkov Detector optimized for:
- Light attenuation length limit
- PMT pressure limit
- Cost (built-in staging)

UNO Collaboration
- 99 Physicists
- 40 Institutions
- 7 Countries

60x60x60m^3 x 3
Total Vol: 650 kton
Fid. Vol: 440 kton (20xSuperK)
# of 20" PMTs: 56,000
# of 8" PMTs: 14,900

Only optical separation

NNN05-Aussois, April 2005
MEMPHYS

-> a very large Laboratory to allow the installation of a Megaton-scale Cerenkov Detector ($\approx 10^6 \, \text{m}^3$)

Present Tunnel

Future Safety Tunnel

Present Laboratory

Future Laboratory with Water Cerenkov Detectors

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Physics reach of Megaton scale Water Cherenkov Detectors

Octant of $\theta_{23}$

Nonzero $\theta_{13}$

$\delta CP$
oscillation effects in $\nu_e$

Pares and Smirnov hep-ph/0309312 (at Sub-GeV range)

$$\frac{\Psi(\nu_e)}{\Psi_0(\nu_e)} - 1 \cong P_2 (r \cdot c_{23}^2 - 1)$$

- $r \cdot s_{13} \cdot c_{13}^2 \cdot \sin 2\vartheta_{23} (\cos \delta_{CP} \cdot R_2 - \sin \delta_{CP} \cdot I_2)$
- $+ 2s_{13}^2 (r \cdot s_{23}^2 - 1)$

$LMA$

interference

$\vartheta_{13}$ resonance

$r$ : $\mu/e$ flux ratio ($\sim 2$ at low energy)

$P_2 = |A_{e\mu}|^2$ : 2$\nu$ transition probability $\nu_e \rightarrow \nu_{\mu\tau}$ in matter

$R_2 = \text{Re}(A_{ee}^* A_{e\mu})$

$I_2 = \text{Im}(A_{ee}^* A_{e\mu})$

$A_{ee}$ : survival amplitude of the 2$\nu$ system

$A_{e\mu}$ : transition amplitude of the 2$\nu$ system
Effect of $\theta_{23}$ after $\nu$ interactions

- $s^2\theta_{12} = 0.825$
- $s^2\theta_{23} = 0.4 \sim 0.6$
- $s^2\theta_{13} = 0.04$
- $\delta cp = 45^\circ$
- $\Delta m_{12}^2 = 8.3e-5$
- $\Delta m_{23}^2 = 2.5e-3$

<table>
<thead>
<tr>
<th>$s^2_{23}$</th>
<th>no osc. with 20yrs stat.error</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.40</td>
<td>0.45</td>
</tr>
<tr>
<td>0.45</td>
<td>0.50</td>
</tr>
<tr>
<td>0.50</td>
<td>0.55</td>
</tr>
<tr>
<td>0.55</td>
<td>0.60</td>
</tr>
</tbody>
</table>

Neutrino 2006, Santa Fe, USA
Discrimination of $\theta_{23}$ octant

\[ s^2\theta_{12} = 0.825 \]
\[ s^2\theta_{23} = 0.4 \text{ or } 0.6 \]
\[ s^2\theta_{13} = 0.00 \sim 0.04 \]
\[ \delta_{CP} = 45^\circ \]
\[ \Delta m^2_{12} = 8.3 \times 10^{-5} \]
\[ \Delta m^2_{23} = 2.5 \times 10^{-3} \]

With 20yrs SK, discrimination is possible for large $\theta_{13}$.

Neutrino 2006, Santa Fe, USA
Discrimination of $\theta_{23}$ octant

$s^2 \theta_{12} = 0.825$
$s^2 \theta_{23} = 0.45$ or $0.55$
$s^2 \theta_{13} = 0.00$ to $0.04$
$\delta c_p = 45^\circ$
$\Delta m^2_{12} = 8.3 \times 10^{-5}$
$\Delta m^2_{23} = 2.5 \times 10^{-3}$

$s^2 \theta_{23} = 0.45$ or $0.55$
$\leftrightarrow s^2 2\theta_{23} = 0.99$

With 20yrs SK, discrimination is very hard.
Discrimination of $\theta_{23}$ octant, $SKx80yrs$

$s^2\theta_{12}=0.825$
$s^2\theta_{23}=0.40 \sim 0.60$
$s^2\theta_{13}=0.00\sim0.04$
$\delta_{cp}=45^\circ$
$\Delta m^2_{12}=8.3e{-5}$
$\Delta m^2_{23}=2.5e{-3}$

With 80yrs SK, discrimination is better and possible for many test points.

80yrs SK ~ 4yrs HK

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Significance for nonzero $\theta_{13}$

$\sin^2 \theta_{13} = 0.00 \sim 0.04$

$\delta_{cp} = 45^\circ$

$\Delta m^2_{21} = 8.3 \times 10^{-5}$

$\Delta m^2_{23} = 2.5 \times 10^{-3}$

Positive signal for nonzero $\theta_{13}$ can be seen if $\theta_{13}$ is near the CHOOZ limit and $\sin^2 \theta_{23} > 0.5$

20yrs SK

3σ for 80yrs SK

~4yrs HK
\[ s^2\theta_{12} = 0.825 \]
\[ s^2\theta_{23} = 0.5 \]
\[ s^2\theta_{13} = 0.00 \sim 0.04 \]
\[ \delta_{\text{CP}} = 0^\circ \sim 360^\circ \]
\[ \Delta m_{12}^2 = 8.3 \times 10^{-5} \]
\[ \Delta m_{23}^2 = 2.5 \times 10^{-3} \]

CP phase could be seen if \( \theta_{13} \) is close to the CHOOZ limit.
Summary

- A large magnetised detector of 50-100 Kton like INO is needed to achieve some of the very exciting physics goals using atmospheric neutrinos.
- It will complement the existing and planned water cherenkov detectors.
- Can be used as a far detector during neutrino factory era.
- R & D for setting up such a detector in India is in progress.

- If $\theta_{13}$ is close to the CHOOZ limit, then next generation water Cherenkov detectors could give us precious information on;
  - octant of $\theta_{23}$
  - nonzero $\theta_{13}$
  - $\delta CP$