India Based Neutrino Observatory Proposal

Goal: To build an underground laboratory for science with neutrino physics as major activity

The Detector: A large mass detector with charge identification capability. The collaboration zeroed on magnetized Iron CALorimeter detector (ICAL)

Detector choice based on
- Technological capabilities available in the country
- Existing/Planned other neutrino detectors in the world
- Modularity and the possibility of phasing
- Compactness and ease of construction
R & D Activities

Phase-I
- Physics Studies
- Detector R & D
- Site Finalisation and Clearances
- Human Resource Development
- Construction of the underground lab and ICAL detector

Phase-II
- Physics with Atmospheric Neutrinos

Phase-III
- Physics with Beams
PUSHEP at South India has been recommended as the preferred site for the underground lab.
The detector

- Magnetised iron calorimeter
- Modular structure - 3 modules
- Module dimension $16m \times 16m \times 12m$
- Detector: $48m \times 16m \times 12m$
- 140 horizontal iron layers interspersed with Glass RPC
- Iron Plate thickness 6 cm
- Gap for RPC trays 2.5 cm

- Sensitive to muons
- Energy determination from
  - Track length
  - Track curvature in a magnetic field
- Direction of parent neutrino from the track
- Charge identification from track curvature in magnetic field
Physics Goals for INO

First phase – measurement of atmospheric neutrino flux
- Reconfirmation of the first oscillation dip as a function of L/E
- Improved precision of oscillation parameters
- Determination of the octant of $\theta_{23}$
- Matter effects and determination of sign of $\Delta m_{31}^2$
- Probing CPT violation, Lorentz violation
- Discrimination between $\nu_\mu - \nu_\tau$ and $\nu_\mu - \nu_s$
- Constraining long range leptonic forces
- 1-100 TeV cosmic muon flux measurement

Second Phase – end detector for beta beams, neutrino factory
- hierarchy, $\theta_{13}$, CP violation

Other possibilities
- Search for $0\nu 2\beta$ in $^{124}Sn$ via cryogenic bolometer (feasibility ongoing)
Atmospheric Neutrinos and INO

Observation of fall and rise of up/down $\nu_\mu$ events

Increased precision of $\Delta m^2_{atm}$
Comparison with Long Baseline Experiments

3σ spread \( (|\Delta m^2_{31}| = 2 \times 10^{-3} \text{ eV}^2, \sin^2 \theta_{23} = 0.5) \).

| \( |\Delta m^2_{31}| \) | \( \sin^2 \theta_{23} \) |
|----------------|----------------|
| current        | 29%            | 33%            |
| MINOS+CNGS     | 13%            | 39%            |
| T2K            | 6%             | 23%            |
| Nova           | 13%            | 43%            |
| INO, 50 kton, 5 years | 10%    | 30%            |

Table refers to the older NO\(\nu\)A proposal; the revised March 2005 NO\(\nu\)A proposal is expected to be competitive with T2K.

M. Lindner, hep-ph/0503101
Ambiguity in Mass Hierarchy

\[ \tan 2\theta_{13}^m = \frac{\Delta m_{31}^2 \sin 2\theta_{13}}{\Delta m_{31}^2 \cos 2\theta_{13} \pm 2\sqrt{2} G_F n_e E} \]

- For \( \Delta m_{\text{atm}}^2 > 0 \) matter resonance in neutrinos
- For \( \Delta m_{\text{atm}}^2 < 0 \) matter resonance in anti neutrinos
- Experiments sensitive to matter effects can probe the mass hierarchy
- Matter effects for \( \Delta m_{\text{atm}}^2 \) channel depend crucially on \( \theta_{13} \)
- Thus both parameters get related
Large matter effects at long baselines

For $\Delta m_{\text{atm}}^2 = 2.5 \times 10^{-3} \text{ eV}^2$, $\sin^2 2\theta_{13} = 0.1$ and the PREM profile $\rho_{av} = 4.13 \text{ gm/cc}$, $E_{res} \simeq 7.5 \text{ GeV}$

$\nu_\mu$ survival probability can rise or fall in matter
Hierarchy Sensitivity in Atmospheric $\nu$ events

For $\Delta m^2_{31} > 0$ matter effect in $\nu_\mu$ and $(N^\text{mat}_{\mu^-} \neq N^\text{vac}_{\mu^-})$

$(N^\text{mat}_{\mu^+} \approx N^\text{vac}_{\mu^+})$

Analysis of Hierarchy Sensitivity in INO

- **Exposure:** $100 \text{ Kt} \times 10 \text{ yr} = 1000 \text{ Kt yr}$
- **Muon event number:** $(\phi_{\mu} \times P_{\mu\mu} + \phi_{e} \times P_{e\mu}) \times \sigma_{CC} \times \epsilon$
- **Detection efficiency:** 87%
- **Charge i.d. of muons:** 100%
- **3-dimensional Honda fluxes**
- **Range studied for matter effects:** $E = 2$ to $10 \text{ GeV}$, $\cos \theta_z = -0.1$ to $-1.0$
- **Muon threshold:** 1 GeV
- **Detector resolution of:** $10^\circ, 15\%$
- **Energy and $\cos \theta_z$ range divided into:** $8 \times 18 = 144$ bins
- **Oscillation parameters uncertainties are taken care of by Marginalization**
Effect of $\delta_{CP}$ on $\chi^2$

Effect of $\delta_{CP}$ on Muon $\chi^2$ insignificant

Problem of $\delta_{CP}$ degeneracy less

With increased width of smearing the event distribution tends to no oscillation distribution.
Effect of Smearing on $\chi^2$

Effect of smearing on muon-$\chi^2$ in INO

With increased energy or angular smearing the $\chi^2$ for muon like events decrease.

Hierarchy sensitivity reduces with marginalization

A. Samanta, 2006
D. Indumathi and M.V.N. Murhyt, PRD, 2005
**Hierarchy Sensitivity: comparative study**

- **INO**: 1 Mtyear (100 kT × 10 years)
  \[ \chi^2 = \chi_{\mu}^2 + \chi_{\bar{\mu}}^2 \]

- **HyperKamiokande**: 1.8 Mtyear (544 kT × 3.3 years)
  \[ \chi^2 = \chi_{\mu+\bar{\mu}}^2 + \chi_{e+\bar{e}}^2 \]

- **LiqAr**: 1 Mtyear (100 kT × 10 years)
  \[ \chi^2 = \chi_{\mu}^2 + \chi_{\bar{\mu}}^2 + (\chi_{e}^2 + \chi_{\bar{e}}^2)_{1-5\text{GeV}} + (\chi_{e+\bar{e}}^2)_{5-10\text{GeV}} \]

<table>
<thead>
<tr>
<th>( \sin^2 2\theta_{13} )</th>
<th>( HK \chi^2 )</th>
<th>( INO \chi^2 )</th>
<th>( \text{LiqAr} \ \chi^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.04</td>
<td>3.6</td>
<td>4.5</td>
<td>13.8</td>
</tr>
<tr>
<td>0.1</td>
<td>5.9</td>
<td>9.6</td>
<td>27.5</td>
</tr>
<tr>
<td>0.15</td>
<td>7.1</td>
<td>16.9</td>
<td></td>
</tr>
</tbody>
</table>

- **LiqAr** type detector has lower energy threshold, better energy smearing and partial charge identification of electrons
  (Gandhi, Ghoshal, Goswami, Umashankar, arXiv:0807.2759)
Deviation of $\sin^2 \theta_{23}$ from maximal value

- $D \equiv 1/2 - \sin^2 \theta_{23}$
- $|D|$ gives the deviation of $\sin^2 \theta_{23}$
- $\text{sgn}(D)$ gives the octant of $\sin^2 \theta_{23}$
- Current $3\sigma$ limits:
  - $|D| < 0.16$ at $3\sigma$ from the SK data
  - No robust information on $\text{sgn}(D)$
Can Earth matter effects determine $|D|$?

$P_{\mu\mu}^m = 1 - P_{\mu\mu}^1 - P_{\mu\mu}^2 - P_{\mu\mu}^3$

$P_{\mu\mu}^1 = c_{13}^m \sin^2 2\theta_{23} \sin^2 \left[1.27(\Delta^m_{32})L/2E\right]$

$P_{\mu\mu}^2 = s_{13}^m \sin^2 2\theta_{23} \sin^2 \left[1.27(\Delta^m_{21})L/2E\right]$

$P_{\mu\mu}^3 = \sin^4 \theta_{23} \sin^2 2\theta_{13}^m \sin^2 \left(1.27\Delta^m_{31}L/E\right)$

- Dependence on $\theta_{23}$ in the form $\sin^4 \theta_{23}$
- Octant sensitivity?

S. Choubey and P. Roy hep-ph/0509197
Also Indumathi et al. hep-ph/0603264
Can Earth matter effects determine $|D|$?

Using atmospheric neutrinos in INO

$|D|$ can be measured to $\sim 17\% (20\%)$ at $3\sigma$ for $s_{13}^2 = 0.04(0.00)$ with 1 MtonY exposure and 50% detector efficiency

S. Choubey, and P. Roy hep-ph/0509197
Resolving the octant ambiguity in INO

Using atmospheric neutrinos in INO

For every non-maximal $\sin^2 \theta_{23}(\text{true})$ there exists a $\sin^2 \theta_{23}(\text{false})$

$$\sin^2 \theta_{23}(\text{false}) = 1 - \sin^2 \theta_{23}(\text{true})$$

S. Choubey and P. Roy hep-ph/0509197
Comparing the Octant Sensitivity of Experiments

Long baseline experiments
No octant sensitivity
- LBL+atmospheric Huber et al hep-ph/0501037
- LBL accelerator + reactor Minakata et al hep-ph/0601258

Atmospheric neutrinos in water Cerenkov detectors
\( \sin^2 \theta_{23} \) (false) can be excluded at 3\( \sigma \) if:
\[
\sin^2 \theta_{23} \text{(true)} < 0.36 \text{ or } > 0.62
\]
Gonzalez-Garcia et al, hep-ph/0408170

Atmospheric neutrinos in large magnetized iron detectors
\( \sin^2 \theta_{23} \) (false) can be excluded at 3\( \sigma \) if:
\[
\begin{align*}
\sin^2 \theta_{23} \text{(true)} &< 0.36 \text{ or } > 0.63 \text{ for } \sin^2 \theta_{13} \text{(true)} = 0.01, \\
\sin^2 \theta_{23} \text{(true)} &< 0.40 \text{ or } > 0.59 \text{ for } \sin^2 \theta_{13} \text{(true)} = 0.02, \\
\sin^2 \theta_{23} \text{(true)} &< 0.41 \text{ or } > 0.58 \text{ for } \sin^2 \theta_{13} \text{(true)} = 0.03, \\
\sin^2 \theta_{23} \text{(true)} &< 0.42 \text{ or } > 0.57 \text{ for } \sin^2 \theta_{13} \text{(true)} = 0.04.
\end{align*}
\]
S.Choubey. and P. Roy hep-ph/0509197
Simulation studies with atmospheric neutrinos are in progress at many collaborating Institutions

- **Nuance Event Generator**
  - Generates atmospheric neutrino events inside the INO detector

- **GEANT Monte Carlo Package**
  - Simulates the detector response for the neutrino events

- **Event Reconstruction**
  - Fits the raw data to extract neutrino energy and direction

- **Physics Performance**
  - Analysis of reconstructed events to extract physics.
INO as a long baseline detector
$P_{e\mu}$ for NH and IH at different baselines

Agarwalla, Choubey, Raychaudhuri, hep-ph/0610333
$P_{e\mu}$ for two values of $\theta_{13}$ at different baselines

\[\sin^2 2\theta_{13} = 0.1\]
\[\sin^2 2\theta_{13} = 0.05\]
The Magic baseline

Agarwalla, Choubey, Raychaudhuri, hep-ph/0610333

- At $\sim 7500$ km $\delta_{CP}$ dependence negligible
- $(\delta_{CP}, \theta_{13})$ and $(\delta_{CP}, sgn(\Delta m_{atm}^2))$ degeneracies vanish
- Clean measurement of $sgn(\Delta m_{atm}^2) \theta_{13}$
The Magic baseline

\[ P_{e\mu} \simeq \sin^2 \theta_{23} \sin^2 2\theta_{13} \frac{\sin^2[(1 - \hat{A})\Delta]}{(1 - \hat{A})^2} \]

\[ \pm \alpha \sin 2\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \sin \delta_{CP} \sin(\Delta) \frac{\sin(\hat{A}\Delta)}{\hat{A}} \frac{\sin[(1 - \hat{A})\Delta]}{(1 - \hat{A})} \]

\[ + \alpha \sin 2\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \cos \delta_{CP} \cos \Delta \frac{\sin(\hat{A}\Delta)}{\hat{A}} \frac{\sin[(1 - \hat{A})\Delta]}{(1 - \hat{A})} \]

\[ + \alpha^2 \cos^2 \theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(\hat{A}\Delta)}{\hat{A}^2} \]
The Magic baseline

\[ P_{\mu\mu} \simeq \sin^2 \theta_{23} \sin^2 2\theta_{13} \frac{\sin^2[(1 - \hat{A})\Delta]}{(1 - \hat{A})^2} \]

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\[ + \alpha^2 \cos^2 \theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(\hat{A}\Delta)}{\hat{A}^2} \]

If \( \sin(\hat{A}\Delta) \simeq 0 \) \( \Rightarrow P_{\mu\mu} \simeq \sin^2 \theta_{23} \sin^2 2\theta_{13} \frac{\sin^2[(1 - \hat{A})\Delta]}{(1 - \hat{A})^2} \)
The Magic baseline

\[ P_{e\mu} \sim \sin^2 \theta_{23} \sin^2 2\theta_{13} \frac{\sin^2[(1 - \hat{A})\Delta]}{(1 - \hat{A})^2} \]

\[ \pm \alpha \sin 2\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \sin \delta_{CP} \sin(\Delta) \frac{\sin(\hat{A}\Delta)}{\hat{A}} \frac{\sin[(1 - \hat{A})\Delta]}{(1 - \hat{A})} \]

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- \( \sin(\hat{A}\Delta) \simeq 0 \Rightarrow L_{\text{magic}} \simeq 7690 \text{ km} \)

Barger, Marfatia, Whisnant, hep-ph/0112119

Huber, Winter, hep-ph/0301257

Smirnov, hep-ph/0610198
The Magical Reach of INO

CERN to INO distance = 7152 km
The Magical Reach of INO

CERN to INO distance = 7152 km

JPARC to INO distance = 6556 km
The Magical Reach of INO

- CERN to INO distance = 7152 km
- JPARC to INO distance = 6556 km
- RAL to INO distance = 7653 km
The Magical Reach of INO

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INO is wonderfully close to magic baseline
CERN-INO distance is equal to 7152 km
CERN-INO Magical Beta-Beam Experiment

- CERN-INO distance is equal to 7152 km
- A golden channel \((P_{e\mu})\) experiment at magic baseline using a \(\beta\) beam as source of \(\nu_e\) and INO as the end detector
- Beta beam spectrum depends on the end point energy of the beta unstable ion and Lorentz boost \(\gamma\)
- The standard Beta-Beam ions \(^{18}Ne\) and \(^{6}He\) would require very large gamma

Agarwalla, Raychaudhuri, Samanata, PLB, 2005
CERN-INO Magical Beta-Beam Experiment

CERN-INO distance is equal to 7152 km

Alternative ions $^8B$ and $^8Li$ have large end-point energy and hence “harder” spectra.

Flux peaks at $E \approx 6$ GeV for $\gamma = 350 - 500$.

Agarwalla, SC, Raychaudhuri, hep-ph/0610333
Conditions For Maximum Matter effect

Large Distance $\Rightarrow$ Large Matter effects
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- Large Distance $\Rightarrow$ Large Matter effects
- Resonance energy

$$E_{res} = \frac{|\Delta m_{atm}^2| \cos 2\theta_{13}}{2\sqrt{2}G_F N_e}$$
Conditions For Maximum Matter effect

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\[ E_{res} = \frac{|\Delta m_{atm}^2| \cos 2\theta_{13}}{2\sqrt{2}G_FN_e} \]

- For $\Delta m_{atm}^2 = 2.5 \times 10^{-3}$ eV$^2$, $\sin^2 2\theta_{13} = 0.1$ and the PREM profile $\rho_{av} = 4.13$ gm/cc, $E_{res} \simeq 7.5$ GeV
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- Maximal oscillations when $\sin^2 2\theta_{13}^m \sim 1$ and $\sin^2 \left( \frac{(\Delta m_{atm}^2)^m L}{4E} \right) \sim 1$ simultaneously

Gandhi, Ghoshal, Goswami, Mehta, Umashanakar, hep-ph/0408361
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Gandhi, Ghoshal, Goswami, Mehta, Umashanakar, hep-ph/0408361

- At the magic baseline, largest oscillations come when $E \sim 6 \text{ GeV}$
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Large Distance $\Rightarrow$ Large Matter effects

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Maximal oscillations when $\sin^2 2\theta_{13} \simeq 1$ and $\sin^2 \left(\frac{(\Delta m_{atm}^2)^mL}{4E}\right) \simeq 1$ simultaneously

Gandhi, Ghoshal, Goswami, Mehta, Umashankar, hep-ph/0408361

At the magic baseline, largest oscillations come when $E \simeq 6$ GeV

CERN-INo $\beta$-beam experiment can capture maximal matter effect
Reach of The CERN-INO $\beta$-beam Experiment

$\sin^2 \theta_{13}^{\text{discovery}}$ for $\theta_{13}$ at $3\sigma$ if

$\sin^2 2\theta_{13}^{\text{true}} \geq 5.1 \times 10^{-4}$

Agarwalla, Choubey, Raychaudhuri, arXiv:0711.1459
Reach of The CERN-INO $\beta$-beam Experiment

\[
\sin^2 \theta_{13}^{\text{true}} \geq 5.1 \times 10^{-4}
\]

\[
\sin^2 \theta_{13}^{\text{true}} \geq 5.6 \times 10^{-4}
\]

Agarwalla, Choubey, Raychaudhuri, arXiv:0711.1459
Reach of The CERN-INO $\beta$-beam Experiment

\[ \sin^2 2\theta_{13} \text{(true)} \geq 5.1 \times 10^{-4} \]

Signal for $\theta_{13}$ at $3\sigma$ if $\sin^2 2\theta_{13} \text{(true)} \geq 5.1 \times 10^{-4}$

Mass Hierarchy at $3\sigma$ if $\sin^2 2\theta_{13} \text{(true)} \geq 5.6 \times 10^{-4}$

Agarwalla, Choubey, Raychaudhuri, arXiv:0711.1459
INO and Neutrino Factory

**ICAL@INO** will be a 50–100 kton Magnetized Iron Calorimeter detector

ideal candidate for a NuFact detector
INO and Neutrino Factory

Sensitivity to $\sin^2 2\theta_{13} \lesssim 2.0 \times 10^{-4}$ (3$\sigma$)

Huber et al., hep-ph/0606199

Best sensitivity comes at the Magic Baseline
INO Time Line

Phase I: 12-18 months
- Draw up detailed design report for tunnel and cavern
- Detailed design report on detector structure, RPCs, pickup electrodes, electronics and power supply system
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Expected to start the first module by 2012
INO: Approval Status

INO Interim Project Report presented to DAE and DST in May, 2005.

A presentation on INO proposal was made to SAC-PM in August 2005.

Interim report sent to panel of International Reviewers in 2006.

It was discussed by the Mega Science Committee set up by Planning Commission in September 2006 and recommended for funding in the XIth 5 year plan starting from April 2007.

It is an "in principle" funding and clearances are sought for environment and forest department.

Budget: ~ 500 crores in INR  (≈ 150 million US Dollars)
Conclusion

A large magnetized iron calorimeter detector has substantial physics potential using atmospheric neutrinos.

- Reconfirmation of L/E dip and precision of $\Delta m_{31}^2$
- Matter effect and Sign of $\Delta m_{31}^2$
- Determination of octant of $\theta_{23}$
- CPT violation, Long Range Forces ..... 

- It will complement the planned water Cerenkov and Liquid Argon Detectors as well as the long baseline and reactor experiments

- In its second phase it can serve as an end detector for a beta-beam or beam from a neutrino factory

- Location is close to the Magic Baseline from all major accelerator facilities

- Clean measurement of hierarchy and $\theta_{13}$

More details at http://www.imsc.res.in/~ino