INO and its Physics Possibilities

Raj Gandhi*

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* For the INO Collaboration
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The proposal is under review both domestically and by an International panel and a final funding decision is expected very soon.
Magnetized calorimeter.

- 140 horizontal iron plates each 6 cm thick, interspersed with Glass RPC.
- Modular structure.
Will fulfill the need of the MONOLITH detector proposed earlier for Gran Sasso.
The Detector . . .

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- Estimated timescale from approval is 5 years for 50 kT, though design may allow earlier operation of completed modules

- Estimated cost is about USD 100 million
The Site

- Height of peak is 2207 m.
- Hydroelectric power project with access roads, large caverns at 500 m depth and 13 km of tunnels already adjoin the proposed site, thus Geotechnical knowledge of area exists.
- Few hours drive from Bangalore International Airport.
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- Observe distinct signatures of matter effects and the Mass Hierarchy in Atmospheric Neutrinos
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- Observe distinct signatures of matter effects and the Mass Hierarchy in Atmospheric Neutrinos
- Make much-needed measurements of VHE muons (10-300 TeV) via the pair meter technique
- Test for CPT violation, Lorentz Invariance and the presence of long-range forces
In its second phase, INO can function as a detector for a neutrino factory exploiting the rich physics potential possible with it due to its muon charge identification capability.

Its distances both from CERN (7145 km) and from JHF (6556 km) are close to the magic baseline distance of 7000 km.
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- Determination of the mass hierarchy
- Detect CP violation in the neutrino sector, in conjunction with a second appropriately positioned detector.
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- Determination of the mass hierarchy

- Detect CP violation in the neutrino sector, in conjunction with a second appropriately positioned detector.

- Improve the precision on $\theta_{13}$ considerably
Measurements of Atmospheric Oscillation Parameters
Clean detection of $L/E$ dip possible within about 2 years of running.
3σ spread ( $\Delta m^2_{13} = 2 \times 10^{-3} \text{ eV}^2$, $\sin^2 \theta_{23} = 0.5$).

|                  | $|\Delta m^2_{13}|$ | $\sin^2 \theta_{23}$ |
|------------------|---------------------|-----------------------|
| current          | 44%                 | 39%                   |
| MINOS+CNGS       | 13%                 | 39%                   |
| T2K              | 6%                  | 23%                   |
| Nova             | 13%                 | 43%                   |
| INO, 50 kton, 5 years | 10%               | 30%                   |

Table refers to the older NOνA proposal; the revised March 2005 NOνA detector is expected to be competitive with T2K.

M. Lindner, hep-ph/0503101
Comparison with Long baseline Experiments

\[ \Delta m_{31}^2 \text{-precision} \]

\[ \sin^2 \theta_{23} \text{-precision} \]

Relative error at 2\( \sigma \)

True value of \[ \Delta m_{31}^2 \] [10\(^{-3}\) eV\(^2\)]

SK+K2K current data

True value of \[ \Delta m_{21}^2 \] [10\(^{-3}\) eV\(^2\)]
Is $\theta_{23}$ maximal?
The difference between U/D ratios for neutrinos and anti-neutrinos is sensitive to the deviation of $\theta_{23}$ from maximality.
Measuring the Deviation of $\theta_{23}$ from maximality . . .

- The difference between U/D ratios for neutrinos and anti-neutrinos is sensitive to the deviation of $\theta_{23}$ from maximality.

- A non maximal $\theta_{23}$ has important implications for model building.
Measuring the deviation of $\theta_{23}$ from maximality

S. Choubey and P. Roy, hep-ph/0509197

Raj Gandhi, NNN06, Sep 21 2006, Seattle – p.14/43
So far we only know $|\Delta m_{31}^2|$ and not its Sign.

Normal ordering ($\delta m_{31}^2 > 0$)  Inverted ordering ($\delta m_{31}^2 < 0$)
The importance of the mass hierarchy lies in its capability to discriminate between various types of models for unification, and thus in its ability to narrow the focus of the quest for physics beyond the Standard Model.
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A large class of GUTS use the Type I seesaw mechanism to unify quarks and leptons. Several positive features are lost if in such models the neutrino hierarchy is inverted rather than normal.
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It would also favour theories utilising the Type II seesaw mechanism with additional Higgs triplets.
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The type of hierarchy impacts the effectiveness of leptogenesis in most theoretical models.

(a) 9700 Km

(b) 7000 Km

$P_{\mu e}$

$P_{\mu \tau}$

$P_{\mu \mu}$

$\Delta m^2_{31} > 0$

Vacuum

$\Delta m^2_{31} < 0$
Measuring the Up/Down Asymmetry

\[ A_N = \frac{U}{D} - \frac{\overline{U}}{\overline{D}} \]

\( \delta = 0.001 \)

\( \delta = 0.002 \)

\( \delta = 0.003 \)

D. Indumathi and M. Murthy, hep-ph/0407336

Plot of Probabilities

\( P(\nu_\mu \rightarrow \nu_\mu) \)

- Vacuum
- \( \Delta_{31} > 0 \)
- \( \Delta_{31} < 0 \)

E (GeV)

6000 km
7000 km
8000 km
10000 km

Raj Gandhi, NNN06, Sep 21 2006, Seattle  – p.20/43
Survival Probability: $\theta_{13}$ sensitivity ...
Results for an Iron Calorimeter type detector
Results: Iron Calorimeter, 1000 kt-yr...

\[
\begin{align*}
\sin^2 2\,_{13}^\theta &= 0.1 \\
\Delta_{31} &= 0.002 \text{ eV}^2
\end{align*}
\]

R. Gandhi et al., hep-ph/0411252
Asymmetry in Up-Down Event Rates...
Results: Iron Calorimeter, 1000 kt-yr...

L = 8000 to 10700 Km, E = 4 to 8 GeV

\[ \Delta_{31} = 0.002 \text{ eV}^2 \]

R. Gandhi et al., hep-ph/0411252
Results: Iron Calorimeter, 1000 kt-yr...

\[ \sin^2 2\theta_{13} = 0.1 \]

\[ L = 6000 \text{ to } 9700 \text{ Km, } E = 5 \text{ to } 10 \text{ GeV} \]

R. Gandhi et al., hep-ph/0411252

\[ L = 6000 \text{ to } 10700 \text{ Km, } E = 4 \text{ to } 8 \text{ GeV} \]

\[ \sin^2 2\theta_{13} = 0.1 \]
Bin by bin $\chi^2$-analysis

Results for a iron calorimeter detector:
- $\chi^2$ analysis of $\mu^-$ event in 24 L/E bins
- 15% energy and 15° angular resolution
- 10% systematic error
- 85% efficiency
- Marginalized over $\Delta m^2_{31}$, $\sin^2 \theta_{13}$, $\sin^2 \theta_{23}$

<table>
<thead>
<tr>
<th>$\sin^2 2\theta_{13}$</th>
<th>$\chi^2_{\text{min}}$ (500 kt yr)</th>
<th>$\chi^2_{\text{min}}$ (1000 kt yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.05</td>
<td>2.7</td>
<td>3.7</td>
</tr>
<tr>
<td>0.1</td>
<td>6.6</td>
<td>8.9</td>
</tr>
</tbody>
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Gandhi et al. work in progress.
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</table>

Gandhi et al. work in progress.

The Importance of Detector Resolution

Petcov and Schwetz, hep-ph/0511277
**Bin by bin $\chi^2$-analysis**

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Gandhi et al. work in progress.

- Comparison with water-Cerenkov detector
  - No charge sensitivity: $N_\mu = N_{\mu^+} + N_{\mu^-}$

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<th>$\chi^2_{\text{min}}$ (6 Mt yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.05</td>
<td>1.9</td>
</tr>
<tr>
<td>0.1</td>
<td>4.4</td>
</tr>
</tbody>
</table>

Gandhi et al., hep-ph/0406145
INO as a Detector for VHE Cosmic Ray Muons
Why study VHE muons from CR?

Such studies could help resolve an important open question regarding the Cosmic Ray Spectrum, i.e. the origin of the knee.
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These studies would be very useful for all UHE neutrino telescopes like AMANDA, ICECUBE etc, since muons and neutrinos at these energies constitute their most important background. At present there is little or no data on the energy spectrum of muons above $\sim 10$ TeV.
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These studies would provide crucial data towards understanding the prompt contribution to VHE muon fluxes.
Muon energy measurement methods which work well in the GeV range (magnetic spectrometry or measuring Cerenkov radiation) are rendered impractical in the TeV range primarily due to requirements of size imposed by the combination of high energies and a steeply falling spectrum.
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The pair meter technique skirts some of these difficulties by relying on a somewhat indirect method, *i.e.* the measurements of the energy and frequency of electron-positron pair cascades produced by the passage of a high energy muon in dense matter.
The Pair Meter Technique

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The cross section for $e^+e^-$ pair production by a muon with energy $E_\mu$ with energy transfer above a threshold $E_0$ grows as $\ln^2(2m_e E_\mu / m_\mu E_0)$, where $m_\mu$ and $m_e$ are the muon and electron masses respectively.
VHE Muon Detection in INO . . .

R. Gandhi and S. Panda, hep-ph/0512179

![Graph 1](image1)

![Graph 2](image2)

Raj Gandhi, NNN06, Sep 21 2006, Seattle – p.31/43
### VHE muons entering INO in 5 years

<table>
<thead>
<tr>
<th>$E_{\mu}(\text{TeV})$</th>
<th>Number of muons per solid angle entering the detector in 5 years</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$E_{\mu}(\text{TeV})$</td>
<td>conv+TIG</td>
</tr>
<tr>
<td>1</td>
<td>$1.035 \times 10^7$</td>
<td>$1.03 \times 10^7$</td>
</tr>
<tr>
<td>10</td>
<td>52486</td>
<td>51282</td>
</tr>
<tr>
<td>50</td>
<td>770</td>
<td>696</td>
</tr>
<tr>
<td>100</td>
<td>127</td>
<td>106</td>
</tr>
<tr>
<td>200</td>
<td>22</td>
<td>16</td>
</tr>
<tr>
<td>300</td>
<td>8</td>
<td>5</td>
</tr>
<tr>
<td>400</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>500</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>600</td>
<td>1.5</td>
<td>1</td>
</tr>
<tr>
<td>700</td>
<td>1</td>
<td>.5</td>
</tr>
<tr>
<td>800</td>
<td>.8</td>
<td>.35</td>
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<td>900</td>
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<td>.25</td>
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<td>1000</td>
<td>.5</td>
<td>.2</td>
</tr>
<tr>
<td>10000</td>
<td>.0025</td>
<td>.0003</td>
</tr>
</tbody>
</table>

Table 2: Number of muons per solid angle entering the detector over 5 years for various energies of the entering muon, $E_{\mu}$.  

R. Gandhi and S. Panda, hep-ph/0512179
### Number of cascades per muon for different thresholds $E_0$ in GeV

<table>
<thead>
<tr>
<th>$E_\mu$</th>
<th>$E_{\mu}^s$</th>
<th>5</th>
<th>10</th>
<th>20</th>
<th>50</th>
<th>100</th>
<th>300</th>
<th>500</th>
<th>1000</th>
<th>5000</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6.1</td>
<td>3.08</td>
<td>2.56</td>
<td>3.78</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>40.26</td>
<td>17.28</td>
<td>10.99</td>
<td>6.43</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>83.16</td>
<td>25.3</td>
<td>17.28</td>
<td>10.99</td>
<td>5.34</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>205</td>
<td>38.58</td>
<td>28.26</td>
<td>19.67</td>
<td>10.99</td>
<td>6.43</td>
<td>2.78</td>
<td>2.56</td>
<td></td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>407.58</td>
<td>50.63</td>
<td>38.58</td>
<td>28.26</td>
<td>17.28</td>
<td>10.99</td>
<td>4.58</td>
<td>3.08</td>
<td>2.56</td>
<td></td>
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<tr>
<td>200</td>
<td>813</td>
<td>64.43</td>
<td>50.63</td>
<td>38.58</td>
<td>25.30</td>
<td>17.28</td>
<td>8.11</td>
<td>5.34</td>
<td>3.08</td>
<td></td>
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<tr>
<td>300</td>
<td>1218</td>
<td>73.3</td>
<td>58.49</td>
<td>45.42</td>
<td>30.8</td>
<td>21.76</td>
<td>10.99</td>
<td>7.46</td>
<td>4.19</td>
<td></td>
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<tr>
<td>400</td>
<td>1624</td>
<td>79.96</td>
<td>64.43</td>
<td>50.63</td>
<td>35.06</td>
<td>25.3</td>
<td>13.39</td>
<td>9.33</td>
<td>5.34</td>
<td></td>
</tr>
<tr>
<td>500</td>
<td>2029</td>
<td>85.33</td>
<td>69.24</td>
<td>54.89</td>
<td>38.58</td>
<td>28.26</td>
<td>15.45</td>
<td>10.99</td>
<td>6.43</td>
<td>2.56</td>
</tr>
<tr>
<td>600</td>
<td>2435</td>
<td>89.85</td>
<td>73.3</td>
<td>58.49</td>
<td>41.58</td>
<td>30.8</td>
<td>17.28</td>
<td>12.47</td>
<td>7.46</td>
<td>2.58</td>
</tr>
<tr>
<td>700</td>
<td>2841</td>
<td>93.76</td>
<td>76.83</td>
<td>61.64</td>
<td>44.21</td>
<td>33.05</td>
<td>18.91</td>
<td>13.82</td>
<td>8.43</td>
<td>2.6</td>
</tr>
<tr>
<td>800</td>
<td>3246</td>
<td>97.23</td>
<td>79.96</td>
<td>64.43</td>
<td>46.56</td>
<td>35.06</td>
<td>20.4</td>
<td>15.06</td>
<td>9.33</td>
<td>2.72</td>
</tr>
<tr>
<td>900</td>
<td>3652</td>
<td>100.33</td>
<td>82.77</td>
<td>66.95</td>
<td>48.69</td>
<td>36.9</td>
<td>21.76</td>
<td>16.21</td>
<td>10.18</td>
<td>2.89</td>
</tr>
<tr>
<td>1000</td>
<td>4057</td>
<td>103.16</td>
<td>85.33</td>
<td>69.24</td>
<td>50.63</td>
<td>38.58</td>
<td>23.02</td>
<td>17.28</td>
<td>10.99</td>
<td>3.08</td>
</tr>
<tr>
<td>10000</td>
<td>40554</td>
<td>174.84</td>
<td>151.24</td>
<td>129.38</td>
<td>103.16</td>
<td>85.33</td>
<td>60.63</td>
<td>50.63</td>
<td>38.58</td>
<td>17.28</td>
</tr>
</tbody>
</table>

Table 3: Number of cascades above thresholds $E_0 = 5, 10, 20, 50, 100, 300, 500, 1000, 5000$ GeV per muon. Here $E_\mu$ is the energy of the muon in TeV entering the detector, and $E_{\mu}^s$ is its corresponding energy in TeV at the surface of the earth, assuming it traversed a depth of rock corresponding to $3.5 \times 10^5 gm/cm^2$. 

R. Gandhi and S. Panda, hep-ph/0512179
Bounds on CPT/Lorentz Violation
Sensitivity of Neutrino-Antineutrino Event Ratios to CPT.....

A. Datta et al, hep-ph/0408179

Raj Gandhi, NNN06, Sep 21 2006, Seattle – p.35/43
Sensitivity of Neutrino-Antineutrino Event Ratios to CPT.....

A. Datta et al, hep-ph/0408179

Raj Gandhi, NNN06, Sep 21 2006, Seattle – p.36/43
The Iron Calorimeter as an End- Detector for a Neutrino Factory
The Utility of a “Magic Baseline Detector”

R. Gandhi and W. Winter, work in progress
The Iron Calorimeter as an End- Detector for a Beta Beam
The proximity to the magic baseline distance leads again to physics uncluttered by CP degeneracies.

One obtains sensitivity to both the hierarchy and to $\theta_{13}$. 
The proximity to the magic baseline distance leads again to physics uncluttered by CP degeneracies.

One obtains sensitivity to both the hierarchy and to \( \theta_{13} \).
Beta Beam Results...

\[ \gamma = 3340 \text{ (Neutrino)} \]
\[ \delta = 90^\circ \]
\[ \Delta m^2 > 0 \]

\[ \gamma = 2000 \text{ (Anti-neutrino)} \]
\[ \delta = 90^\circ \]
\[ \Delta m^2 < 0 \]

S. Agarwalla, A. Raychaudhuri and A. Samanta, hep-ph 0505015

Raj Gandhi, NNN06, Sep 21 2006, Seattle -- p.41/43
Beta Beam results.....

S. Agarwalla, A. Raychaudhuri and A. Samanta, hep-ph 0505015
INO, a 50-100 kT magnetized iron calorimeter would usefully buttress the presently planned program of neutrino experiments worldwide.

Using atmospheric neutrinos, a 100 kT detector has the potential to illuminate one of the most important questions in neutrino physics, the mass hierarchy.

It would provide improved precision on atmospheric neutrino parameters, improved bounds on CPT/Lorentz violation, crucial data on VHE muons for the CR and PQCD communities and, in its second phase, be an excellent end detector for neutrino factories/beta beams.

At present INO, after an intensive feasibility study, is close to a final funding decision.
I thank my collaborators, A. Datta, P. Ghoshal, S. Goswami, P. Mehta and S. Uma Sankar