Physics potentials of a magnetized iron calorimeter detector

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For the INO collaboration

SNOW2006
Magnetized Iron Calorimeter Detector

Currently feasibility study for such a detector is underway in India by the India-Based Neutrino Observatory (INO) collaboration.

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

MONOLITH collaboration had earlier proposed similar design
The detector

- Magnetised iron calorimeter (∼ 50kT)
- 140 horizontal (vertical) iron layers interspersed with Glass RPC
- Modular structure

- 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
Current Activities

- Detector R & D
- Physics Studies
- Detector Simulation
- Data Acquisition System
- Site Survey
- Human Resource Development

Interim Report submitted to funding agencies
Cost Estimates and Time Schedule

Cost

- Lab. Construction \(\sim 90 \text{ crores INR} \) (1 crore = 10 million)
- Detector \(\sim (200 \text{ (iron)} + 200 \text{ (others)}) \text{ crores in INR} \)

Total cost \(\sim 500 \text{ crores in INR} \) (1 Euro \(\approx\) INR 50)

Time Scale: \(\sim 5\) years from approval

Details: INO interim report, http://www.imsc.res.in/~ino
Site

Two sites were considered – Rammam in North India and PUSHEP in South India.

PUSHEP is recommended for ease of accessibility, less seismicity.

Geotechnological studies are going on.
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

Second Phase – end detector for beta beams, neutrino factory
- hierarchy, $\theta_{13}$, CP violation
- CERN to INO baseline $\sim 7000$ km, the magic baseline
INO as a long baseline detector
Disappearance of $\nu_\mu$ vs L/E

$$\frac{N_{up}(L/E)}{N_{down}(L/E)} \approx P_{\mu\mu}$$

$$= 1 - \sin^2 2\theta_{23} \sin^2 \Delta_{31} \frac{L}{4E}$$

Expect to determine $\Delta_{31}$ with 10% precision
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
Ambiguity in Mass Hierarchy

- Hierarchy difficult to determine in superbeams
- Sensitivity limited by correlation and degeneracies
- Synergistic use of experiments
- Use of Magic Baseline

M. Lindner, hep-ph/0503101
Problem of $\delta_{CP}$ degeneracy less at longer baselines

Significant matter effect in $P_{\mu\tau}$ at 9700 km and for $E \sim 5$ GeV

Genuine three flavour effect

Impact on $P_{\mu\mu}$

$P_{\mu\mu} = 1 - P_{\mu e} - P_{\mu\tau}$

At 7000 km drop in $P_{\mu\mu}$ induced by $P_{\mu e}$

At 9700 km rise in $P_{\mu\mu}$ induced by $P_{\mu e}$ and $P_{\mu\tau}$

R. Gandhi et. al, PRL, 2005
Determining Hierarchy by Atmospheric Neutrinos

Using $\mu^-$ rates in magnetized iron calorimeter detectors like INO

$$\frac{\phi_{\mu^-}}{\phi^0_{\mu^-}} \approx P_{\mu\mu} + rP_{e\mu}$$

$$= P_{\mu\mu}(1 - r) - rP_{\mu\tau} + r$$

For $\Delta m^2_{31} > 0$ matter effect in $\nu_\mu$ ($N_{\mu^+}^{\text{mat}} \approx N_{\mu^+}^{\text{vac}}$)
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$$r = \frac{\phi_{\mu^0}^e}{\phi_{\mu}^0}$$

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

$L = 8000 \text{ to } 10700 \text{ Km}, E = 4 \text{ to } 8 \text{ GeV}$

Gandhi et al., hep-ph/0411252
Palomarez-Ruiz, hep-ph/0406096
Murthy, Indumathi hep-ph/0407336

Srubabati Goswami, SNOW2006 – p.12/20
Determining Hierarchy by Atmospheric Neutrinos

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$$r = \phi_{e\mu}^0/\phi_{\mu}^0$$

For $\Delta m^2_{31} > 0$ matter effect in $\nu_\mu$ ($N_{\mu^+}^{mat} \approx N_{\mu^+}^{vac}$)

3-4$\sigma$ signal for matter effects at $\sin^2 2\theta_{13} = 0.1$ for 1000kTy using the total event rates for fixed values of parameters

Parameter uncertainties spoil the sensitivity
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 $\Delta m_{31}^2$, $\sin^2 \theta_{13}$, $\sin^2 \theta_{23}$

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Gandhi et al. work in progress.
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Gandhi et al. work in progress.

Effect of Smearing

Petcov and Schwetz, hep-ph/0511277
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Comparison with water-Cerenkov detector

- No charge sensitivity: $N_\mu = N_{\mu^+} + N_{\mu^-}$

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Gandhi et al., hep-ph/0406145
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 $|D|$?

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

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

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

\[ P_{\mu\mu}^3 = \sin^4 \theta_{23} \sin^2 2\theta_{13}^m \sin^2 (1.27\Delta_{31}^m L/E) \]

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

- **Nuance Event Generator**
  - Generates of 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.
Conclusion

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

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

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

- Can be used as a far detector for neutrino factories

Should be an International Facility