India-based Neutrino Observatory (INO)
The INO underground facility will host a 50 kt magnetized Iron CALorimeter (ICAL) detector to study atmospheric neutrino oscillations.

- Proposed to be located in the Bodgi West Hills in the South India.
- ~2 km rock cover in all directions to shield from cosmic muon background
- Primary goals: Identification of the neutrino mass ordering, precision measurements of atmospheric parameters, probes of non-standard physics like sterile neutrino, dark matter, magnetic monopoles, CPT violation, Non-Standard Interactions

The ICAL Detector
- 151 layers of 5.6 cm iron plates (interaction target) alternative with 150 layers of resistive plate chambers (RPCs, active detector elements)
- ~1.3 Tesla magnetic field to enable muon charge identification (distinguish μ± from e±)
- Optimized to detect Q(1-10) GeV muons with good energy, direction resolutions
- Energy of hadron showers may be reconstructed, albeit with a coarse resolution
- Oscillation physics sensitivity primarily from the νμ disappearance channel.

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Sterile Neutrinos
Mixing matrix with 4 neutrinos

\[ U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} & U_{\mu4} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} & U_{\tau4} \end{pmatrix} \]

Possible 4v Mass Ordering configurations

[Diagram of possible mass ordering configurations]

We expect \(|U_{e4}|^2, |U_{\mu4}|^2, |U_{\tau4}|^2 \ll 1; |U_{\mu4}|^2 \approx 1\).

Oscillograms for the νμ → νe Channel
\[ \Delta P_{\mu e} = P_{\mu e} (4f) - P_{\mu e} (3f) \]

Fast oscillations would be averaged out by finite detector resolutions

Zenith Angle Distribution of Events
Suppression of muon event counts

N-N-1 : Suppression of muon events for all zenith angles
N-N-2 : Non-trivial dependence of suppression on zenith angle

Benchmark Values: \(|U_{e4}|^2 = 0.025, |U_{\mu4}|^2 = 0.05\)

Factors affecting |Uμe|2 Sensitivity

For \(\Delta m^2_{41}<10^{-2} eV^2\), detection is possible only if oscillations to develop.

\[ \Delta m^2 = \Delta m^2_{41} \]

Features due to the interference between these two frequencies

Only the averaged oscillation effects observable for \(\Delta m^2_{41} \gtrsim 1 eV^2\)

The muon energy and direction resolutions in ICAL enhance the sensitivity in this \(\Delta m^2_{41}\) regime.

The sensitivity to |Uμe|2 depends only mildly on the 4v mass ordering scheme.

The most conservative sensitivity estimate on |Uμe|2 are those with |Uμe|2 = 0.

Comparison of the ICAL |Uμe|2 Sensitivity with Current Limits

ICAL can improve upon the current limits on |Uμe|2 for \(\Delta m^2_{41} \sim 10^{-2} eV^2\) and all the way down to \(10^{-5} eV^2\).

Determining magnitude and sign of \(\Delta m^2_{41}\) (if sterile neutrinos exist)

Precision measurement of \(\Delta m^2_{41}\)

\[ \Delta m^2_{41} (true) = +10^{+eV^2}(N-N-2) \]

Exposure: 500 kt-year

Strongly disfavored due to the absence of MSW resonance

When the true scenario is N-N-2, it is possible to rule out N-N-1,N-3 and N-1.

Sign of \(\Delta m^2_{41}\)
Marginalized over all \(\Delta m^2_{41}\) of the wrong sign

Sensitivity to sign of \(\Delta m^2_{41}\) for \(\Delta m^2_{41} \gtrsim 10^{-2} eV^2\)

Hadron energy information (3D analysis) and charge identification (CID) crucial

Concluding Remarks

- ICAL (and atmospheric neutrino experiments in general) sensitive to a wide range of \(\Delta m^2_{41}\) even as low as \(10^{-3} eV^2\).

- ICAL sensitivity to the magnitude and sign of \(\Delta m^2_{41}\) is maximum in the range \((0.5 - 5) \times 10^{-3} eV^2\)

- Spectral information (zenith angle distribution), hadron energy information (3D analysis) and charge identification (CID) crucial