INO as atmospheric and magic baseline detector

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Abstract. We present a status report on the proposed India-based Neutrino Observatory (INO). We focus on the physics studies possible with an iron calorimeter detector (ICAL) at INO. Such a detector would make precision measurements of neutrino oscillation parameters with atmospheric neutrinos in the first phase with the possibility of acting as a far-end detector of a future neutrino factory or beta beam. This talk was given at the 12th International Workshop on Neutrino Factories, Super beams and Beta Beams, 2010 (Nufact10), in Oct 2010.

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INTRODUCTION

This talk reports on the current status of the proposed India-based Neutrino Observatory (INO) underground laboratory [1] and the physics reach of the proposed Iron Calorimeter (ICAL) detector to be located there. One of the main objectives of this collaboration is a study of neutrino oscillation physics with atmospheric neutrinos. The laboratory is also uniquely located to provide the right (near-magic baseline) distance to a future possible neutrino factory beam (from a muon storage ring or beta beam) in CERN or Japan.

In Section 2 we briefly outline the current knowledge of neutrino oscillation parameters. In Section 3 we discuss details about INO: the site, the choice of detector, and related R&D. In Sections 4, 5 and 6 we discuss the physics reach of the detector with reference to atmospheric neutrinos as well as future possible long-baseline neutrino studies. Section 7 concludes with an outlook.

NEUTRINO OSCILLATION PROPERTIES

Neutrino oscillation studies have by now definitively established that neutrinos are massive and that different flavours mix; however, the masses are not well-known. Oscillation studies only determine the *mass-squared differences* $\Delta m^2_{ij} = m^2_i - m^2_j$ (see Fig. 1) and the *mixing angles* θ_{ij}. It is not established whether θ_{23} is away from maximality. The mass ordering of the third state is not known. There are three distinct possibilites[2]: $m_1 \sim m_2 \sim m_3 \sim 0.2$ eV (degenerate hierarchy); $m_1 < m_2 \ll m_3$ (normal hierarchy); $m_3 \ll m_1 < m_2$ (inverted hierarchy). Determination of the neutrino mass hierarchy is one of the important issues in neutrino physics and such a determination typically depends on θ_{13} being non-zero. Only an upper limit is established for this angle so far, $\sin^2\theta_{13} < 0.032$ (2σ).

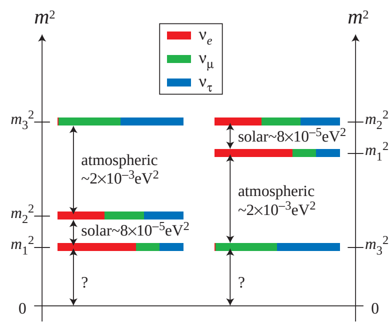

FIGURE 1. Schematic showing the possible mass hierarchies and neutrino mixings [2].

INO STATUS REPORT

The primary focus of INO is physics with atmospheric *muon neutrinos*. This implies construction of a magnetised iron detector (called ICAL), with Resistive Plate Chambers (RPCs) as the sensitive detector element, that is sensitive to the energy, direction and charge (sign) of muons that are produced by charged-current interactions of the detector material with such neutrinos. This automatically implies that such a detector (perhaps suitably upgraded) will also be a suitable choice as a far-end detector of a long-base-line experiment.

Detector R & D is proceeding apace; a 1/1000 scale prototype is located at Kolkata; work on a 1/100 model will begin soon.

The site for the laboratory is about 1.3 km below the Bodi West Hills, in Tamil Nadu, South India, about 100 km west of the city of Madurai, with the portal at 9°58′N, 77°16′E. Apart from the caverns to house ICAL and associated command/control systems, there will be smaller caverns to locate other detectors (such as for neutrinoless double beta decay) in future, all being accessed by a single drive-in tunnel about 2 km in length.

An associated centre for high energy physics will be located in Madurai. The proposal is awaiting final technical clearances (environment and AEC for financial sanction) but is approved in-principle.

The proposed detector

The primary experiment proposed at INO is the study of atmospheric neutrinos with an iron calorimeter with magnetic field (ICAL). There is currently a preliminary study on-going for neutrino-less double beta decay measurements with a tin cryogenic detector.

The detector design consists of 3 modules (to facilitate ease of construction) with 150 layers of 5.6 cm thick iron plates, with transverse dimensions of 16×16 m^2, separated by a 4.0 cm air gap containing RPCs or glass spark chambers which are the active detector elements. There will be about 30,000 RPCs (of dimension 2×2 m^2) with nearly 4 million readout channels of associated electronics. The iron is magnetised to 1–1.4 T. It has good charge resolution and tracking and energy resolution, especially for muons. Energy of hadrons can be reconstructed as well, but rather coarsely. Hence a significant INO-Industry interface is necessary and has already been developed. Details of the detector and its components have been discussed elsewhere.

PHYSICS AND SIMULATIONS WITH ATMOSPHERIC NEUTRINOS

Phase I mainly involves a study of atmospheric neutrinos with the ICAL detector. Atmospheric neutrinos, of both e and μ type, have a large range in energy E and path-length traversed L. There is an up-down symmetry in the flux of some-what higher energy neutrinos (in the absence of neutrino oscillations) while the up-going neutrinos are depleted due to oscillation. The detector is most sensitive to muons from charged-current (CC) interactions. All hadrons leave similar signatures in ICAL, while electrons leave few traces. These tracks are then analysed for their sensitivity to neutrino oscillation parameters.

Atmospheric neutrino events are generated with the NUANCE neutrino generator[3] using the HONDA flux[4] with some input oscillation parameters Δm^2_{32}, θ_{23}, and θ_{13}. The last determines matter-dependent effects which can be measured from charge-identification.

In particular, the results shown have been generated with GEANT3 [1]. The codes have now been ported to GEANT4 and verified. The track recognition and reconstruction codes have been significantly improved, especially for muons, and hence we expect an improvement over the results we have. The new simulations are still to be completed. Finally, efforts are also on to generate events with the GENIE neutrino generator.

The precision that can be reached with 6 years' exposure, with a 1 T constant magnetic field in the y-direction, is $|\Delta m^2_{32}| \sim 20\%$; $\sin\theta^2_{23} \sim 60\%$; see Fig. 2.

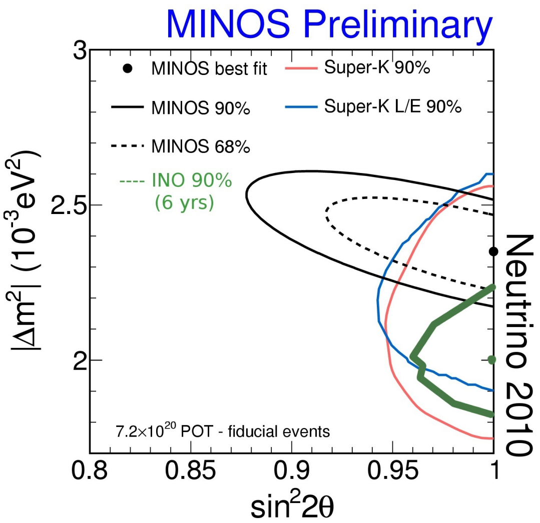

FIGURE 2. Shown are the 90% CL contours in the 2-flavour Δm^2–$\sin^2\theta$ space with the Super-K zenith angle as well as L/E results[5] and recent MINOS data[6], with the INO 6 years' data contour added by hand.

Matter effects with atmospheric neutrinos

Matter effects involve the participation of all three (active) flavours; and hence involve both $\sin\theta_{13}$ and the CP phase $\delta_{\rm CP}$. The key point to note is that there is very little sensitivity to $\delta_{\rm CP}$ over the relevant E, $\theta_{\rm zenith}$ range. Matter effects are therefore sensitive to the mass ordering of the 2–3 states[7, 8, 9], provided θ_{13} is sufficiently large; see Fig. 3.

The sensitive parameter is the difference asymmetry, which is the difference of the up/down ratios of neutrino and antineutrino event rates (charge identification is crucial for this measurement), as can be seen from Fig. 3. Studies show that the mass hierarchy can be determined to 90% CL or better if $\theta_{13} > 6^\circ$; however, the measure-

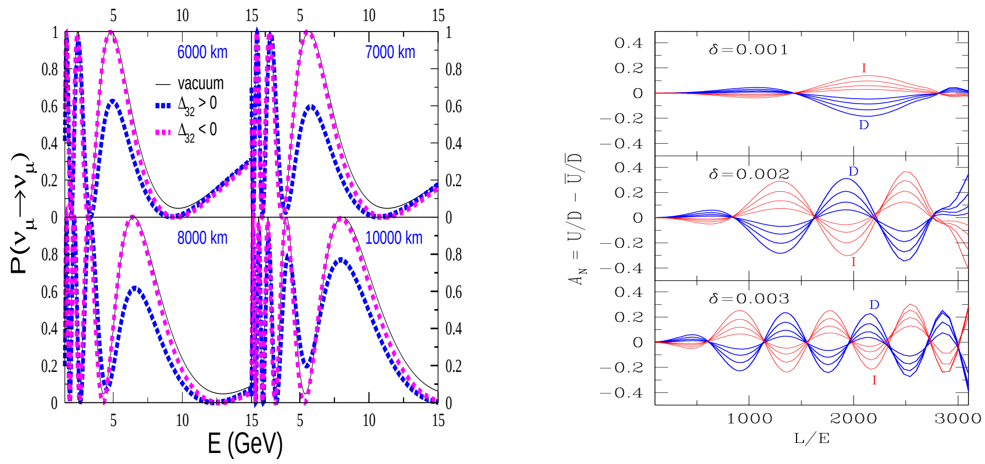

FIGURE 3. Dependence on the sign of Δm^2_{32} of the muon neutrino survival probability, $P_{\mu\mu}$, as a function of L and E (Left). The difference asymmetry for different values of θ_{13} (Right). The curves with larger envelope correspond to increasing θ_{13} from 5–11° in steps of 2°. The darker lines (direct/normal hierarchy) are out of phase with the lighter lines (inverted hierarchy) for all values of $\delta \equiv |\Delta m^2_{32}|$.

ment needs large exposures.

With exposures of 500 kton-years, a 90%CL result is obtained for $\sin^2 2\theta_{13} > 0.09$ (10% R_θ, R_E) or for $\sin^2 2\theta_{13} > 0.07$ (5% R_θ, R_E). Larger exposures of about 1000 kton-years are required [8, 9] for smaller θ_{13} or worse reslutions: $\sin^2 2\theta_{13} > 0.07$ (10% R_θ, 15%R_E) or $\sin^2 2\theta_{13} > 0.05$ (5% R_θ, R_E). Here R_θ, R_E denote the zenith angle and E resolutions of the detector.

The experiment is also sensitive to deviations of the octant of θ_{23} from maximality. Deviations of 20% from maximality can be measured at 99% CL with 1000 kton-year exposure provided $\sin^2\theta_{13} > 0.015$ (see Fig. 4). Results are much poorer for inverted hierarchy and for a solution in the second octant, and will be strongly improved using neutrino-factory beams.

Other physics studies

Other measurements that can be probed with atmospheric neutrinos are the discrimination of active to sterile oscillations from "muon-less events". Long-range leptonic forces can be constrained by probing the matter-dependent term in the oscillation probability even in the absence of U_{e3}. Differences in neutrino and anti-neutrino rates in the detector, apart from contributing differently to matter effects, are themselves of interest due to the recent MINOS/LSND/MiniBooNe data [10].

It is clear that ICAL will be sensitive to oscillation parameters to better accuracy than the current Super-K. Also, it may have the edge on MINOS, depending on the true values of the oscillation parameters. However, ICAL is unique in its sensitivity to the neutrino mass hierarchy, *independent of the CP phase*.

Cosmic ray muons are a signal, not background, at high energies, due to pair-production (pair meter technique). The muon charge ratio at high energies also gives information on meson production by primary cosmic rays, for example, π^+/π^-, K^+/K^-, ratios, etc., which have been recently measured by MINOS [11].

PHYSICS WITH LONG-BASE-LINE NEUTRINOS

In the future, INO can focus on neutrinos from future possible neutrino factories[12] with an upgraded ICAL detector, suitable because of its muon/charge sensitivity, as a far-end detector. One of the important issues is whether the 1–3 mixing angle is zero or not. If $\sin\theta_{13} \neq 0$, one can look for a determination of $\sin\theta_{13}$ itself, sign of Δm^2_{32}, and measurement of the CP violating phase δ.

The standard route involves wrong sign muon detection as a signal of oscillation, so backgrounds are low. INO is located at roughly 7300 km from CERN and 6600 km from JHF. This is very close to the magic baseline, where the event rate is *independent* of the CP phase $\delta_{\rm CP}$, when $\sqrt{2}G_F n_e L = n\pi$. So $L \sim 7400$ km [13].

The degeneracies associated with $\delta_{\rm CP}$–Δm^2_{32} and $\delta_{\rm CP}$–$\sin^2\theta_{13}$ are lifted at the magic baseline, so there is greater sensitivity to both θ_{13} and the magnitude and sign of Δm^2_{32}.

The results shown below are generic to an iron calorimeter detector located at the magic baseline. In particular, for $10^{-4} < \sin^2 2\theta_{13} < 10^{-2}$, the mass hierarchy can be determined [14] for all $\delta_{\rm CP}$.

The sign of Δm^2_{32} (hierarchy sensitivity) can also be

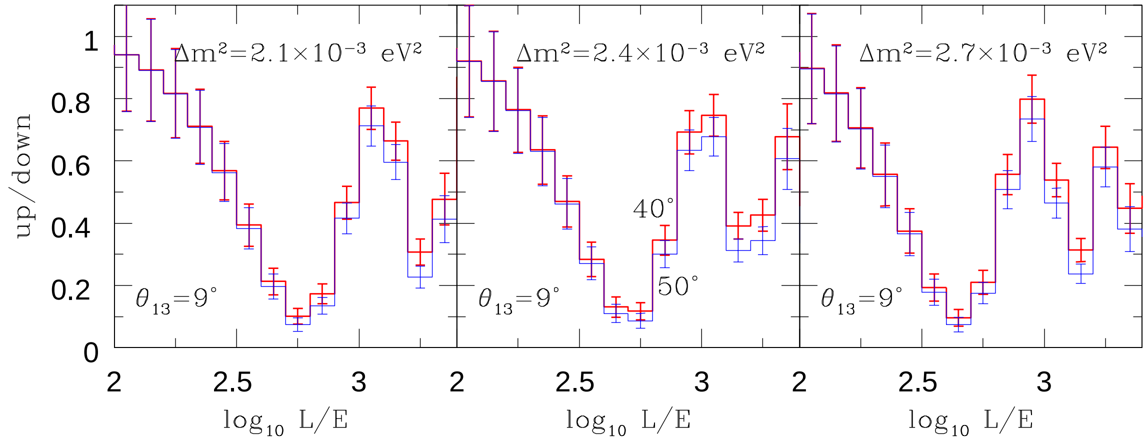

FIGURE 4. Senstivity to the octant of θ_{23} for a fairly large value of $\theta_{13} = 9°$.

determined from observing wrong sign μ [15], as seen in Fig. 5. In contrast, it is seen that there is hardly any sensitivity to the CP phase near the magic baseline. Hence, such data can provide clean separation of matter and CP violation effects.

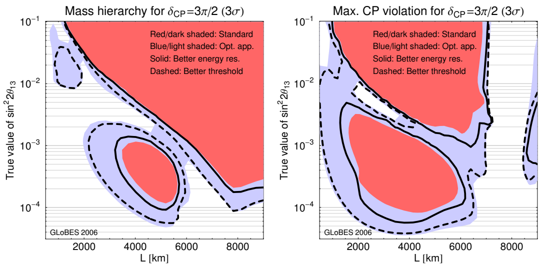

FIGURE 5. Sensitivity to hierarchy and CP violation as a function of baselength with a 50 GeV muon factory beam [15].

MAGIC BASELINE BETA BEAMS

Beta beams are pure $\nu_e(\overline{\nu}_e)$ (from ^{8}B; ^{8}Li sources, so detection of muons clearly indicate oscillation. Since the end-point energies are low, $\sim$ 13 MeV, large boosts are needed. For instance, $\gamma \sim 250, 500$ for B and Li, so this remains a technically challenging scenario. Since muons are already a signal for oscillation, there is much less dependence on charge identification.

The sensitivity of such beams with magic baselines and a detector with INO-type characteristics has been extensively studied [16]. Some results for hierarchy and θ_{13} reach are shown below in Fig. 6.

The effect of adding both neutrino and antineutrino channels is to constrain θ_{13} in such a way that the wrong hierarchy is rejected down to values of $\sin^2 2\theta_{13}$ more than 15–20 times smaller! Detailed issues such as the effect of varying $\delta_{\rm CP}$ have also been studied.

Many of these results are to be redone for the INO-specific detector geometry. Such studies are in progress.

OUTLOOK

The collaboration is hoping for quick clearances and movement on the INO construction front.

The physics case studies look good, but need strengthening by detailed simulations which are now in progress.

Atmospheric neutrinos provide sensitivity to 2–3 mixing parameters, although not to θ_{13}. In particular, if θ_{13} is large enough, it is capable of a δ_{CP}-independent determination of the mass hierarchy. Non-oscillation physics is possible via study of high energy cosmic muons.

ICAL (or an upgraded version) at INO is well suited (both because of its physical characteristics such as charge identification capability and its large mass, and its unique near-magic-baseline location) to be a far-end detector for a future beam facility. Hence there is also a good case to explore the physics of ICAL with muon factory beams and/or beta beams.

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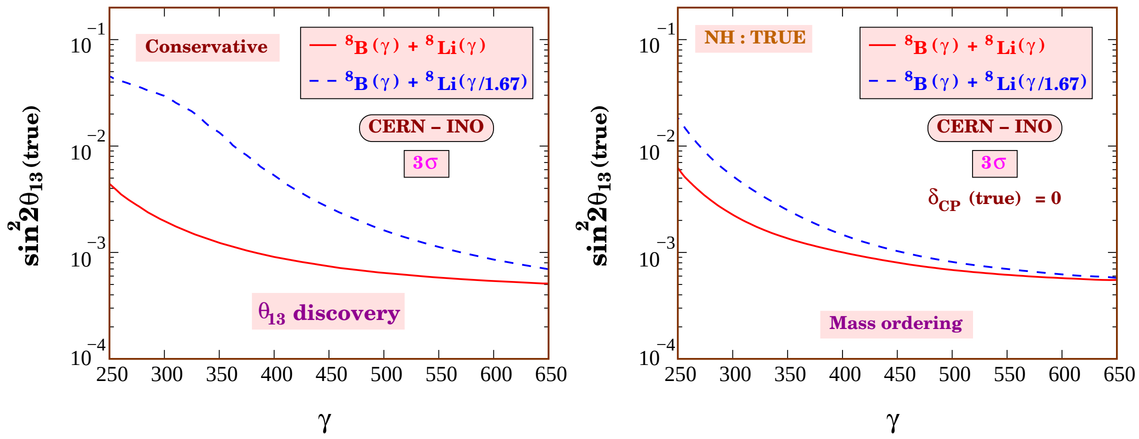

FIGURE 6. 3σ sensitivity/discovery reach with both ν and $\overline{\nu}$ beams with 1.1(2.9) $\times 10^{18}$ useful decays/year, over 5 years.

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