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India-based Neutrino Observatory (INO)

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Abstract. We present some physics possibilities with an iron calorimeter detector (ICAL) and a status report on the feasibility study to construct such a detector at a future possible India-based Neutrino Observatory (INO). This talk was given at the workshop on high energy physics phenomenology, WHEPP-8, in Jan. 2004, at IIT Bombay.

Keywords. Underground neutrino laboratory; iron calorimeter; atmospheric neutrinos; neutrino oscillations.

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1. Introduction

The INO Collaboration is presently engaged in a feasibility study to locate a neutrino laboratory in India. One of the main objectives of this collaboration currently is the study of neutrino oscillation physics with atmospheric neutrinos.

The INO Collaboration includes several institutes and universities in India and has been funded by the Department of Atomic Energy (DAE), India for the feasibility study. This study includes possible location(s) for INO, physics issues and associated choice of detector; subsequent detector R&D, and detailed physics simulations.

In §2 we discuss the choice of neutrino source(s) and detector. We highlight some features of the active elements (RPCs) of an iron calorimeter (ICAL) detector and its magnetisation. We briefly describe possible locations of such an underground neutrino observatory.

In §3 we present some detailed physics issues with both atmospheric neutrinos and neutrino-factory neutrinos, i.e., possible long-baseline physics.

2. Status report

The primary focus of ICAL at INO [1] is physics with atmospheric *muon neutrinos.* This implies construction of a detector 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 upgraded in terms of fiducial volume) will also be a suitable choice as a far-end detector of a long-baseline experiment.

The first stage (feasibility) of the study, which is ongoing, is for 2 years. It includes detector R&D, physics studies and simulations, site survey, and human resource development, including construction and testing of a prototype detector. If funded, the construction of both the laboratory and the detector will be undertaken in the next stage.

2.1 *Detector*

The currently proposed detector is an iron calorimeter with magnetic field (ICAL). The ICAL geometry is similar to that of MONOLITH [2].

The detector design consists of 140 layers of 6 cm thick iron plates, with transverse dimensions of 32 × 16 m, separated by a 2.5 cm air gap containing RPCs or glass spark chambers which are the active detector elements. 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.

RPC efficiency studies are being conducted with different gas mixtures (of argon, freon and isobutane (8%)). About 90% efficiencies with nanosecond timing at voltage around 9 kV are obtained with smaller size detectors; typical results are shown in figure 1. Larger detectors of about 1 × 1 m^2 are being tested for timing, efficiency, noise, cross-talk, etc.

A scaled-down version of the magnet (1/100 model) is ready and its performance checks with a 2D code simulation. A 3D code is in place and the magnet design (with copper coils) is being finalised.

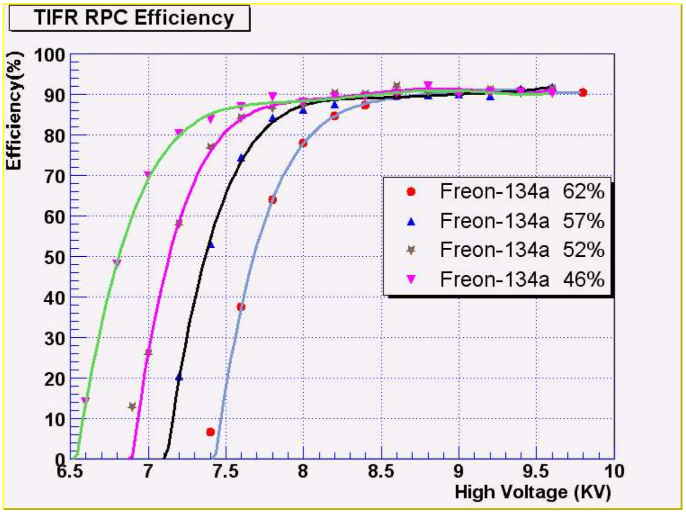

Figure 1. RPC efficiency as a function of gas mixture.

2.2 *Site selection*

Two sites are being evaluated at present for their suitability for locating INO. They are in Singara in South India and Rammam in northeast India.

1. The site at Singara near the town of Masinagudi (Lat. 11.5°N, Long. 76.6°E) under the Nilgiri Mountains in the southern peninsular shield in South India, is adjacent to a hydel project PUSHEP (Pykara ultimate stage hydroelectric project). The vertical overburden is around 1.3 km. All-around cover of more than 1 km exists, with the laboratory cavern to be dug at the end of a tunnel of about 2 km length. The site is geologically stable (seismic zone 2) with uniform granitic (charnockite) rock medium of 2.72 gm/cc mean density. It is close to the Cosmic Ray Laboratory of TIFR and the Radio Astronomy Centre of TIFR, both in the hill station, Ooty. It is easily accessed from the nearby big cities (with airports) like Kozhikode (Calicut), Coimbatore and Bangalore, with excellent industrial and academic infrastructure. A detailed geological survey of the region is complete.
2. Rammam (Lat. 27°N, Long. 88°E) under the Himalayas, is in the Darjeeling District of West Bengal in northeast India. A tunnel of length 3–5 km can reach an overburden of 1.4–1.8 km. The rock quality at the tunnel/cavern location is mostly gneiss rock of 2.8 gm/cc mean density with quartz and feldspar intrusions and is in seismic zone 4. A detailed survey is now complete.

Both sites are excellent for an underground neutrino laboratory. A critical evaluation of the relative advantages and disadvantages of both sites with respect to the physics goals and practical aspects is going on, in order to select one of these sites for the INO lab.

3. Physics 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 somewhat higher energy neutrinos (in the absence of neutrino oscillations) so that the up-going neutrino rates in a bin around a zenith angle θ can be normalised by the down-going rates [3] in a bin around $\theta \leftrightarrow \pi - \theta$. This is demonstrated in figure 2.

The main components of the simulation package used in this study are:

1. NUANCE neutrino event generator [4] that generates atmospheric neutrino events inside ICAL. A simplified ICAL detector geometry has been encoded in the NUANCE generator.
2. GEANT package that simulates the detector response for the neutrino event, that is, propagates the muons and hadrons through the detector volume.
3. Event reconstruction of energy and direction of muons and energy of hadrons in order to recover neutrino energy and direction.
4. Physics performance, that is, analysis of reconstructed events to extract physics.

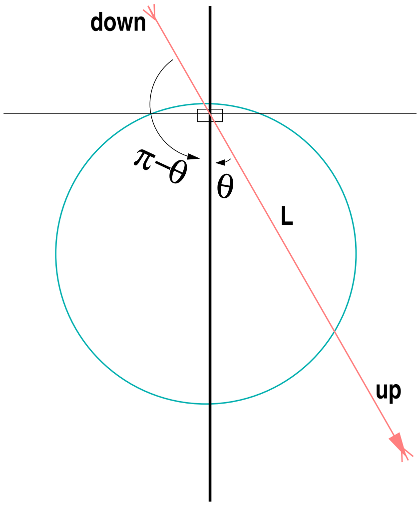

Figure 2. Mirror symmetry in zenith angle dependence of atmospheric neutrino flux implies that (at larger energies) the up-coming neutrino flux in a bin around θ is the same as that of down-going neutrinos in a bin around $(\pi - \theta)$.

One-line status summary: Programs are in place and are being tested; 'data' have been generated with NUANCE for atmospheric neutrinos and are being analysed.

(a) *Events generation*: Events are generated using HONDA flux [5] with some input oscillation parameters δ_{23}, θ_{23}, and θ_{13}. The last determines matter-dependent effects which can be measured from charge identification; we will only show results with $\theta_{13} = 0$ here and refer the reader to several articles that have discussed matter effects [6–8]. For neutrino energies greater than 0.8 GeV, neutrino CC events of interest are roughly generated in equal proportions via quasi-elastic, resonant and DIS processes. All results are shown for five years of accumulated CC events. Typically interesting events have $E > 1$–2 GeV and so the proportion of DIS events in the final sample is somewhat higher than the others.

A major issue, yet to be studied, is the mis-identification of pions as muons from NC as well as a subset of CC events and electron CC events.

(b) *Events analysis*: In the presence of oscillations, the ratio of up-coming to down-going event rates in a given L/E bin is given as

$$\frac{\text{Up rate}}{\text{Down rate}} = P_{\mu\mu} = 1 - \frac{\sin^2\theta_{23}}{2}\left(1 - R\ \cos 2.54\,\delta_{23}\frac{L}{E}\right). \tag{1}$$

Here the up-event rate is normalised by the down-rate in a bin with a path length $\tilde{L}$ such that the corresponding zenith angle is $\theta_{\text{dn}} \leftrightarrow \pi - \theta_{\text{up}}$ in that bin, as discussed earlier. This ratio, which should have been close to the muon neutrino survival probability $P_{\mu\mu}$ is smeared out due to finite detector resolution effects. This smearing is particularly noticeable at large L/E.

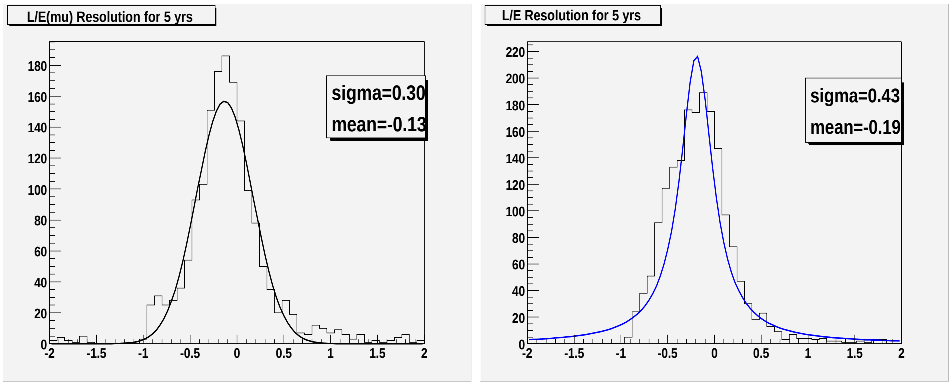

Figure 3. L/E resolution from reconstruction of muons only (left); from complete reconstruction (right).

The resolution function is given by the Lorentzian

$$R(x = L/E) = \frac{1}{\pi}\left(\frac{\sigma/2}{(\sigma/2)^2 + (x - x_0)^2}\right),$$

σ is the width in L/E of the ICAL detector. Contributions to σ come from spread in reconstruction of both L and E of generated events which are propagated in the GEANT-simulated detector. The energy of the neutrino is approximated by $E_\nu \sim E_\mu + E_{\mathrm{h}}$ where E_{h} is the total energy deposited in hadrons, while the direction of the neutrino is approximated by the muon direction alone. Figure 3 shows the L/E resolution of the simulated ICAL detector. The resolution with muons alone is shown on the left. When hadrons are included, the total reconstructed L/E is compared with that of the original neutrino on the right, in the figure.

The resolution obtained, with a magnetic field of 1 T is

$$\Delta\frac{L}{E} = 0.215\,\frac{L}{E}.$$

This is improved as the programs, especially the treatment of hadrons, have since been improved. Note that NUANCE includes final-state interactions in its code as well; this affects the hadron energy.

The resolution obtained, in the absence of magnetic field, for muons only, is $\Delta L/E = 0.18L/E$. This was applied to a sample of events generated using the mixing parameters,

$$\delta_{23} = 3\times 10^{-3}\ \mathrm{eV}^2;\quad \sin^2 2\theta_{23} = 1.0.$$

The sample was binned for its up/down event ratio as a function of L/E and fitted to the theoretical expression in eq. (1) to obtain a best fit to the oscillation parameters of

$$\delta_{23} = (3.3^{+0.3}_{-0.6})\times 10^{-3}\ \mathrm{eV}^2;\quad \sin^2 2\theta_{23} = 0.98^{+0.02}_{-0.07}.$$

The binned data and the fit to it is shown in figure 4.

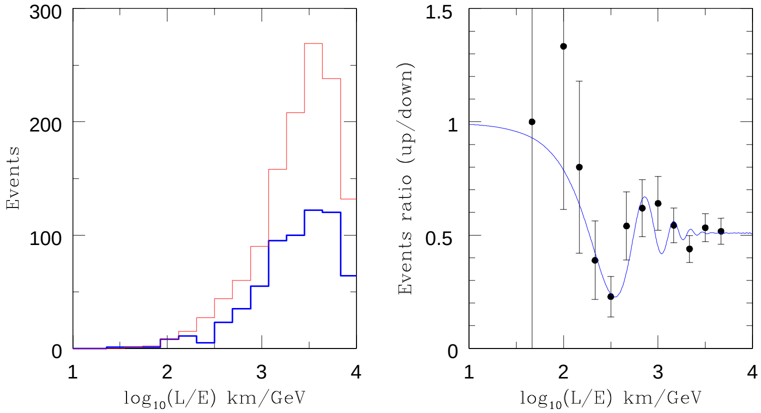

Figure 4. Left: up/down events as a function of L/E. Right: up/down ratio as a function of L/E along with a best-fit curve with parameters as shown/given in text.

(c) *Comments on resolutions*: The worst data are at small L/E (small number of events). The use of magnetic field improves the event rate here. Sensitivity to this small L/E region is still to be studied. One possibility is to look at *vertical* planes of iron. However, it has been subsequently found that this adds events to the very low L/E bin where the resolution is poor as well as the down-going events are also oscillated. Various refinements are still being tested.

(d) *Physics results with NUANCE*: We now present results directly from the NUANCE output, unlike that in figure 4, where the result of full simulation was shown. We use the resolution of the detector as obtained from propagation of muons/hadrons in the simulated detector and reconstruction of their energies and direction. However, we do not apply any other cuts (other than fiducial volume cuts). These arise mainly from finite reconstruction efficiencies (about 40%). We present results using constant $\sin^2 2\theta_{23} = 1$ and $\delta_{32} = 2, 3, 5, 8 \times 10^{-3}$ eV^2. Note that the up/down ratio is sensitive to magnitude of the mass-squared difference and so no charge identification is required here (both neutrino and anti-neutrino events have been added, although the cross-section for the latter is 2–3 times smaller, so there are fewer μ^+ events).

Results are shown in figures 5–8. In all cases it is seen that the error on the mass-squared difference is quite small (less than a few per cent); this improves for lower mass-squared, near 2×10^{-3} which is currently favoured by Super-K analysis. These data will improve the allowed ranges of both parameters δ_{32} and θ_{23}. Note also that ICAL is sensitive to even smaller δ_{32} than shown here; MINOS [9], for example, is unlikely to pinpoint these parameters (or find oscillations) if δ_{32} is smaller than 2×10^{-3} eV^2. On the other hand, the next-generation JPARC experiment [10] will have good sensitivity down to these values of oscillation parameters.

Note added: Due to the large range in E and L available, it turns out that atmospheric neutrinos at ICAL yield limits on the 1–3 mixing angle through matter effects. In particular, if $\sin^2 2\theta_{13} > 5°$, it is possible to determine the neutrino mass hierarchy at ICAL, although the exposure required is large, about 500 kt-years [6–8].

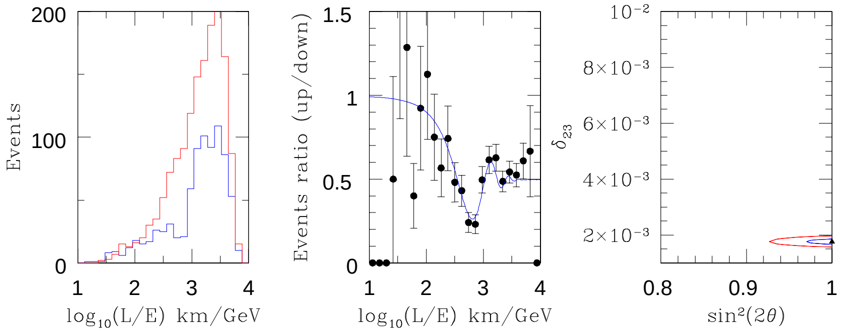

Figure 5. Analysis of five years up/down events with two-flavour oscillations $\delta_{23} = 2 \times 10^{-3}$ eV^2 and $\sin^2 2\theta_{23} = 1$.

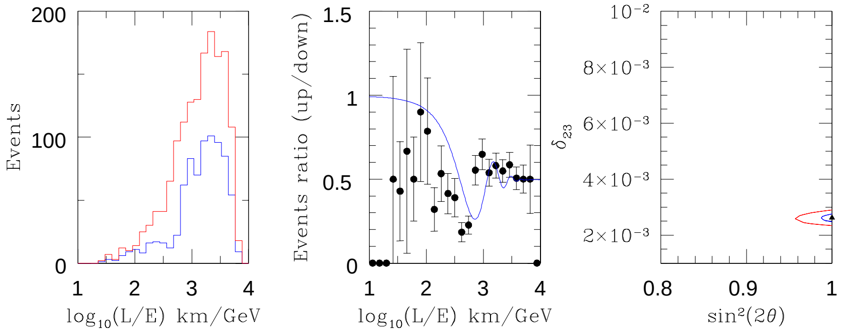

Figure 6. Analysis of five years up/down events with two-flavour oscillations $\delta_{23} = 3 \times 10^{-3}$ eV^2 and $\sin^2 2\theta_{23} = 1$.

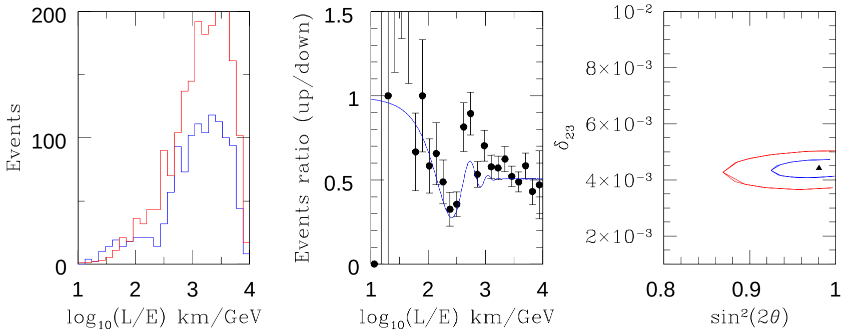

Figure 7. Analysis of five years up/down events with two-flavour oscillations $\delta_{23} = 5 \times 10^{-3}$ eV^2 and $\sin^2 2\theta_{23} = 1$.

4. Physics with long-baseline neutrinos

Phase II of INO will focus on neutrinos from neutrino factories with an upgraded detector (ICAL++) which can be a far-end detector for long baseline experiments. Large L means large E (20 GeV or more), for seeing interesting oscillation

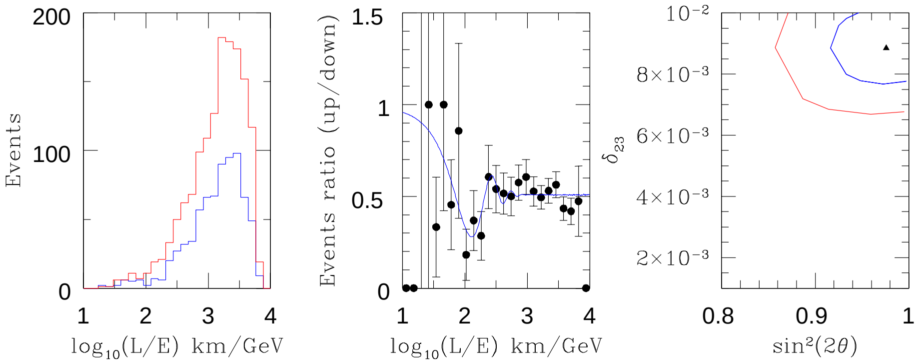

Figure 8. Analysis of five years up/down events with two-flavour oscillations $\delta_{23} = 8 \times 10^{-3}$ eV^2 and $\sin^2 2\theta_{23} = 1$.

phenomena. Such a neutrino beam is far off into the future, but lots of work is going on (see neutrino oscillation industry web-page). More importantly, the detector should be sensitive to muons in such an experiment, and ICAL is therefore suitable. One of the important issues that such an experiment will address 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 the (23) mass-squared difference $\delta_{32} = m_3^2 - m_2^2$,
- CP violation through a CP-violating phase δ that occurs in the mixing matrix when there are three active coupled neutrino species.

The calculation assumes a muon detection threshold of 2 GeV with an energy resolution of 5%. All measurements involve wrong sign muon detection, so backgrounds are low. The wrong sign muon detection is made possible by knowing precisely the beam composition. Suppose the beam contains $\nu_{\rm e}$ and $\overline{\nu}_\mu$. Then the latter give μ^+ in the detector. However, if the $\nu_{\rm e}$ in the beam *oscillate* to ν_μ on the way to the detector, the signal detected will be muons of the opposite sign μ^-. Since backgrounds are low, just 10 wrong sign events per kt is considered a good signal for oscillation.

The reach of $\sin\theta_{13}$, that is, the sensitivity to this parameter, is shown in figure 9. Possible baselines are from JHF, CERN, and FermiLab, to either PUSHEP or Rammam sites for INO. Two particular combinations, from JHF to Rammam and FermiLab to PUSHEP, are shown in the figure. It is seen that the really long baseline almost across the Earth from FermiLab (passing through Earth's core) has a tremendous reach in $\sin\theta_{13}$ (Note: the sine of the angle and not its square is plotted here.) Results are shown for 32 and 50 kt detectors assuming 10^{19} and 10^{21} muon decays per year respectively.

The sign of δ_{32} is also known from observing wrong sign μ, as shown in figure 10. The baselines shown in figure 10 are from JHF to Beijing, Rammam and PUSHEP respectively. Finally, the sensitivity to the CP-violating phase δ is shown in figure 11 as a function of baselength.

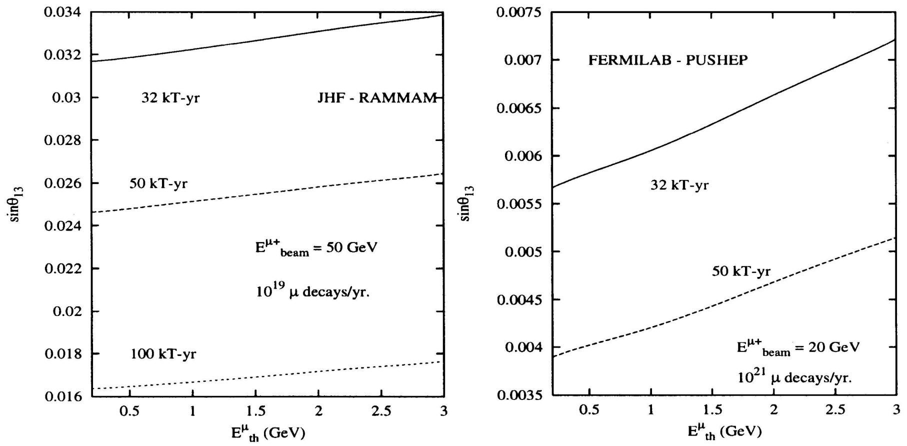

Figure 9. $\sin\theta_{13}$ reach for different muon energies.

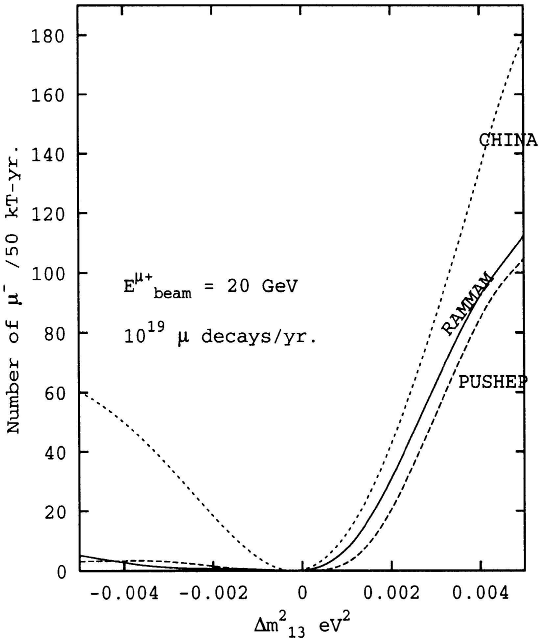

Figure 10. Sign of δ_{32} and sensitivity for different baselengths.

5. Outlook

The ICAL detector seems a good choice to study atmospheric neutrinos with a possible upgrade as a far-end detector of long-baseline neutrino factory neutrinos. Proof-of-principle working of RPC (sensitive elements of the detector) has been shown and more are being tested. Magnet studies are underway as well. Hence the

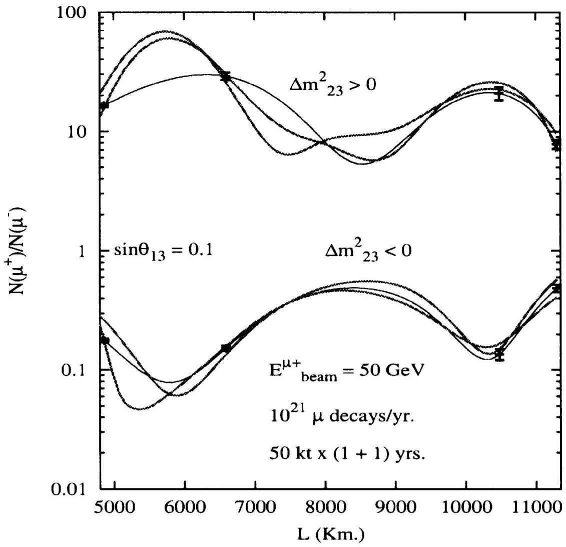

Figure 11. CP violation: δ vs L. Results are shown for $\delta = 0, \pm\pi$.

detector prototype is ready for construction; the electronics design for the prototype is also ready and is being tested.

Two possible sites have been identified; both seem good options. A committee is in the process of evaluating the relative merits of each site. Detector simulations are being done. Programs are in place and are being tested.

(a) *Atmospheric neutrino programme*: ICAL will be sensitive to oscillation parameters to better accuracy than current Super-K. Also, it may have the edge on MINOS if δ_{23} is smaller than expected, although JPARC has better accuracy. It is sensitive to 1–3 mixing angle and also neutrino mass hierarchy [6–8].

(b) *Accelerator neutrino programme*: ICAL++, with a suitable beam from future neutrino factory, is sensitive to $\sin^2 2\theta_{13}$, sign of δ_{23}, and CP phase. The JHF-PUSHEP baseline is near magic: it may provide clean separation of matter and CP-violation effects.

(c) *The INO Collaboration*: An MoU is in place with several institutes funded/aided by the DAE. Phase I studies with atmospheric neutrinos are almost complete; Phase II with neutrinos from neutrino factory are to be studied in more detail. The feasibility study is in full swing; the project report is being written. In short, the outlook looks good!

This is a massive project: we are looking for active collaboration from both within India and abroad.

References

[1] M V N Murthy and U A Yajnik, *Pramana – J. Phys.* **55**, 347 (2000), http://www.imsc.res.in/~ino

[2] N Y Agafonova *et al*, The MONOLITH proposal, LNGS P26/2000, CERN/SPSC 2000-031, August 2000, http://castore.mib.infn.it/~monolith/proposal/
[3] P Picchi and F Pietropaolo, ICGF RAP. INT. 344/1997, Torino 1997 (CERN preprint SCAN-9710037)
[4] The NUANCE Neutrino Generator, D Casper, *Nucl. Phys. Proc. Suppl.* **112**, 161 (2002), http://www.ps.uci.edu/∼nuint/nuance/default.htm
[5] M Honda, T Kajita, K Kasahara and S Midorikawa, *Phys. Rev.* **D64**, 053011 (2001)
[6] Sergio Palomares-Ruiz and S T Petcov, arXiv:hep-ph/0406096
[7] D Indumathi and M V N Murthy, arXiv:hep-ph/0407336
[8] Raj Gandhi, Pomita Ghoshal, Srubabati Goswami, Poonam Mehta and S Uma Sankar, arXiv:hep-ph/0408361
[9] A Para, preprint arXiv:hep-ph/0005012
C Andreopoulos, P Stamoulis and G Tzanakos, NuMI-Note-ATM_NU-990, UA/Phys/HEP/11-05-2003, http://www-numi.fnal.gov/
[10] Y Itow *et al*, arXiv:hep-ex/0106019, http://neutrino.kek.jp/jhfnu/
[11] For the Super-K Collab.: Masaki Ishitsuka, talk given in NOON04, Feb. 2004