Status report on INO

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Abstract. The current status of the India based Neutrino Observatory (INO) is summarized. The main physics goals are described followed by the motivation for building a magnetised iron calorimetric (ICAL) detector. The charge identification capability of ICAL would make it complementary to large water Cerenkov and other detectors worldwide. The status of the design of the 50 kton magnet, the construction of a prototype ICAL detector, the experience with resistive plate chambers which will be the active elements in ICAL and the status of the associated electronics and data acquisition system will be presented.

1. Introduction

The cosmic ray programme initiated by Bhabha was carried forward through the setting up of an underground laboratory in the deepest mine of the Kolar Gold Fields (KGF) in the 50's. Atmospheric neutrinos were first detected here by a TIFR-Osaka-Durham collaboration and also by a team led by Reines working in a South African gold mine [1]. During the late 70s the TIFR-Osaka group set up an experiment at KGF to search for proton decay [2]. By the late eighties, however, mining the gold at KGF became economically unviable and the deepest portions of the mine were closed down. The group then moved to accelerator based high energy physics experiments at Fermilab. In order to revive the experimental culture in high energy physics (HEP) in the country, it was suggested that an underground laboratory be set up with a flagship experiment aimed at measuring neutrino properties. Since there is no domestic accelerator suitable for HEP it was felt that a large detector for atmospheric neutrinos would address this need. An India-based Neutrino Observatory (INO) collaboration was formed in 2002 through the initiative of the Department of Atomic Energy and it was decided, in view of the complementarity with other neutrino detectors worldwide, to build a large iron calorimetric (ICAL) detector. This would build on the proposal for a similar detector by an Italian group [3].

The first phase would involve the construction of a 16 kton iron calorimetric detector. Phase 2 would involve construction of the remaining two 16 kton modules and their use to make atmospheric neutrino and antineutrino measurements. Finally, when this phase is successfully completed, it would be appropriate to bid to be the far detector, at the magic baseline from CERN and Japan, for a beam from a neutrino factory.

An interim project report was submitted to the Department of Atomic Energy on the 1^{st} of May, 2005. In 2006 an updated version [4] was reviewed, very favorably, by 7 international experts. Presently the collaboration has about a hundred members from about 20 plus institutes and Universities

2. Physics goals, choice of detector and site

Some of the important physics issues and questions that the ICAL detector, measuring atmospheric neutrinos, will address are :

1. Observation of oscillatory pattern, fall and rise of muon neutrino flux with L/E, and a precise measurement of neutrino oscillation parameters.
2. Search for matter effects leading to a determination of the sign of Δm^2_{23}. While this has a discovery potential its viability depends crucially on the magnitude of θ_{13} which will be determined by other ongoing/planned reactor experiments.
3. Whether θ_{23} is 45°; or <45° or >45° (octant ambiguity).
4. Constrain leptonic CP phase δ_{CP}, if θ_{13} is non-zero.

If the neutrino factory becomes a reality, a detector such as the one envisaged for INO, could be one of the far detectors in its second phase of operations. The INO site also happens to be at the "magic baseline" of ∼7200 km from two potential sites for a future Neutrino Factory viz. ∼6560 km from JPARC in Tokai, Japan and ∼7150 km from CERN at Geneva, Switzerland. Together with a "near" detector, at say 3000 km, the CP violating phase could be determined.

It may be mentioned that two other initiatives are being planned for the INO underground laboratory. The feasibility study for a neutrinoless double beta decay search using a ^{124}Sn based cryogenic bolometric detector is ongoing. There is also a proposal to house a 500 kV accelerator targeting measurements of nuclear reaction cross sections of astrophysical interest.

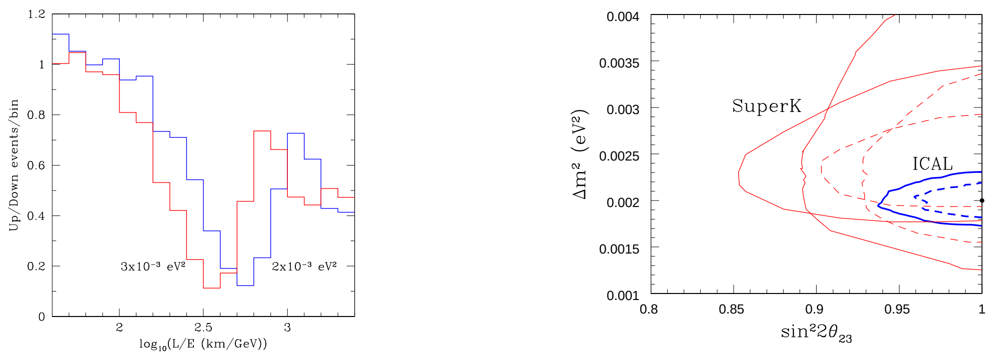

Figure 1. Left: Ratio of upward and downward going neutrinos as a function of L E. Right: Exclusion plot of Δm^2_{23} and $\sin^2_2\theta_{23}$ comparing the SK result and that expected from ICAL.

The first measurements on atmospheric neutrinos at INO would aim at observing directly the oscillations through the fall and rise of the ν_μ and $\overline{\nu}_\mu$ survival probability. Fig. 1 shows the ratio of the simulated upward and downward going muons produced in charged current interactions of neutrinos for two values of Δm^2_{23}. Also shown is an exclusion plot of Δm^2_{23} and $\sin^2 2\theta_{23}$ comparing the regions excluded by the Super Kamiokande (SK) experiment and the expected result from a 250 kton.year exposure of ICAL.

If θ_{13} is greater than 7° it would be possible to fix the neutrino mass hierarchy using the matter effect and the ability to distinguish ν_μ and $\overline{\nu}_\mu$ induced μ^- and μ^+ events [5]. Fig. 2 shows the appearance and survival probabilities for a muon neutrino as a function of the neutrino energy at 2 distances for the normal and inverted mass hierarchies. Also shown on the right are the L/E plots of simulated muons of either charge for a normal hierarchy and an exposure of 1000 kton.years. While the matter effect depletes μ^- the μ^+ spectrum is essentially unaffected.

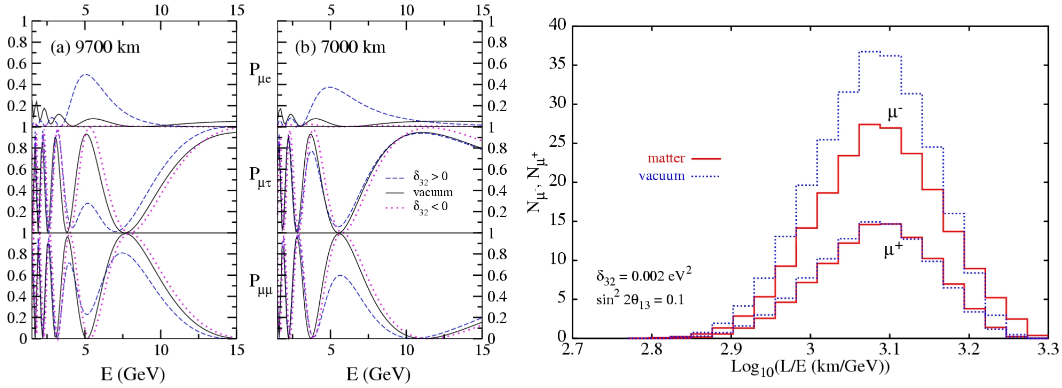

Figure 2. Left: Appearance and survival probabilities for muon neutrinos Right: $\mu^{\pm}$ events for the normal mass hierarchy and an exposure of 1000 kton.yr for a window in L and E.

For the inverted mass hierarchy the situation reverses. A more comprehensive discussion of the physics possibilities at INO may be found in Ref. [4].

Keeping in mind the physics reach of a potential detector, and its complementarity with neutrino detectors worldwide, a large magnetized iron calorimeter measuring atmospheric neutrinos seemed to be the best option. A low energy threshold ICAL detector using thin iron sheets as the target material for neutrinos would increase its dimensions while the use of very thick iron plates would increase the energy threshold. Though the choice of ∼6 cm thick iron plates in ICAL results in an energy threshold of a few hundred MeV atmospheric and accelerator produced muon neutrinos can be studied fruitfully while keeping its size reasonable. A proposal [3] for a similar detector, called MONOLITH, was made by an Italian group but was not funded. The need for such a detector with its inherent charge discrimination capability, allowing it to distinguish between μ^+ and μ^- produced through the charged current interaction of ν_μ and $\bar{\nu}_\mu$, respectively, was stressed in a recent APS study [6]. Such a detector is complementary to the water Cerenkov detectors such as SuperKamiokande and smaller magnetized iron calorimetric detectors measuring neutrinos produced at accelerators at relatively short baselines, such as the MINOS experiment[7].

A magnetized iron calorimeter is an attractive option if charge identification of the muons following a charged current interaction with the target nucleus is required. A magnetic field of about a 1 to 1.5 tesla can be rather easily obtained, using a suitably configured DC current carrying coil for excitation, in soft iron or steel with low carbon content. The superconducting magnet option was also looked into but would have intricacies and associated problems which are not warranted by the detector requirement.

A reasonably precise measurement of the energy-momentum of the interacting atmospheric neutrino is required for a precise measurement of L/E on an event by event basis. This can be done by tracking the charged muon, produced via the charged current neutrino-nucleus interaction, in many layers of a position sensitive detector. The directional information, up or down going, can be obtained for muons which may or may not stop in ICAL through a fast time (sequence) measurement of the individual detector elements. The total area required to be covered is about 10^5 m^2. Of the two possibilities *viz.* gas detectors operated in the avalanche or streamer mode and plastic scintillators with fibre readout, a choice of the former was made. Among the various options in gas detectors the resistive plate chamber (RPC) seems to be a good choice due to its good position and time resolution, ease of construction in large numbers, ruggedness, low cost/unit area, and operational experience in other large experiments. It may be mentioned that the RPC option, while having a smaller capital cost and larger running cost, is at present estimated to 40% cheaper than the scintillator option for a 10 year run. The R&D work on the glass RPC detector including the associated subsystems involving gas circulation, electronics and data acquisition is ongoing. Substantial progress has been made including identifying problems and possible solutions.

Two possible sites for INO were identified in consultation with the Geological Survey of India. One was at Rammam (Lat. 11.5° N, Long. 76.6° E) near Darjeeling in West Bengal and another at PUSHEP, Masinagudi (Lat. 27.4° N, Long. 88.1° E), near the foothills of the Nilgiris in Tamilnadu. An in depth study of the advantages and shortcomings of each site was made by two teams. A site selection committee consisting of physicists, a civil engineer and geologists was formed. Criteria were set to decide the suitability on the basis of depth, seismicity, proximity to industrial centres, access by road etc. This committee looked into all aspects and recommended that Masinagudi was the preferred site for INO.

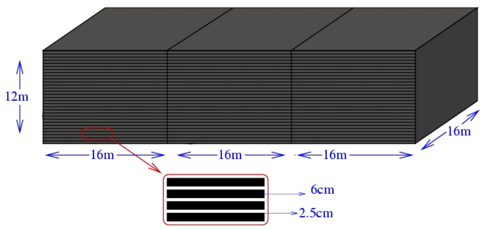

Figure 3. Schematic view of the 50 kton iron calorimeter detector consisting of 3 modules each having 140 layers of iron plates.

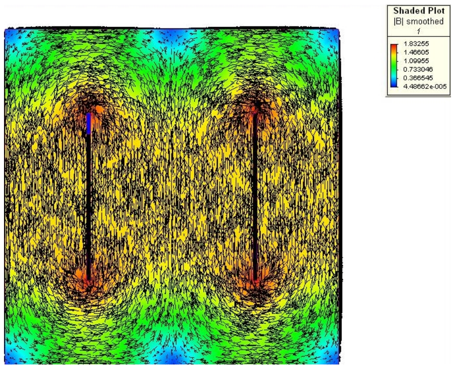

Figure 4. Field lines in a horizontal (x-y) plane of any of the iron plates, the arrows denote the field direction.

3. Status of the project

The conceptual design of ICAL has been made and has a modular structure. Each module weighing 16 kton has a size of 16m×16m×12m and comprises of 140 layers of a unit cell consisting of a 6 cm thick soft iron/low carbon steel plate and a 2.5 cm layer of a X-Y position sensitive resistive plate chamber (RPC). The magnetic field generated with the help of two sets of DC-current carrying coils will be $\sim$1.3 tesla. A schematic of the 50 kton detector is shown in Fig. 3.

The main design criteria for the ICAL magnet are piecewise magnetic field uniformity, modularity, optimum copper-to-steel ratio and access for maintenance. As mentioned above a preliminary design of the 16 kton module has been made using the commercial finite element based software Magnet 6.26 [8], for some configurations of the current carrying coils. Based on these calculations the presently preferred configuration was arrived at. For such a magnet a design with the field returning within the iron plates seems optimal. Two basic geometries can be conceived viz. one with cylindrical symmetry (as in MINOS) and another having a rectangular geometry (as proposed by the Monolith collaboration). We decided to design around a rectangular geometry.

The magnetic field maps of the simulation for the 16 kton ICAL magnet (Fig. 4) show a smooth variation over the single layer of soft iron. For more details see Ref. [4]. The effect of gaps between smaller plates used to tile each layer have been studied. Gaps of 2 mm and 10 mm lead to a reduction in the field by ∼3 and 30%. Ways of minimising this are being looked into.

As mentioned earlier the active detector elements will consist of 2 m×2 m glass (or bakelite) RPCs with X- and Y-position sensitivity ($\sigma_X, \sigma_Y \sim$2 cm) and a time resolution $\sigma_t \sim$1 nsec. Glass and bakelite RPCs R&D is being pursued at Mumbai (mainly TIFR) and Kolkata (mainly SINP). Glass RPCs (size ∼ 30 cm ×30 cm) have been working in the avalanche mode for about 2 years. A similar trend is seen with 1 m× 1 m glass RPCs built for the prototype ICAL detector. We have not had the same success with 1 m^2 glass RPCs operated in the streamer mode. In the area of bakelite RPC R&D the use of silicone oil to coat a locally available variety of bakelite seems to improve its longitivity and performance and appears promising.

The gas mixing and circulation system has been developed in collaboration with a local vendor and, apart from a few teething problems, has performed quite satisfactorily. A collaborative project to develop a closed loop gas circulation system, including a condenser-purifier, is also being pursued. Similarly vendors for the conductive coating on the outer walls for applying the high voltage, polycarbonate spacers and buttons and gas inlet/outlet connections have been developed. A close coordination with local industry for perfecting various industrial processes needed in the manufacture of reliable and rugged RPCs will be necessary.

A test stack of twelve 1 m^2 glass RPCs has been set up at TIFR and used to track cosmic muons (Fig. 5). The cosmic muon trigger was provided by plastic strip scintillator detectors placed above and below the RPC stack. The front end electronics including fast preamplifiers, trigger logic and data acquisition system has been designed and built in-house. This will be used in the prototype ICAL detector. Experience with the 1 m^3 prototype detector should provide inputs for the design of the electronics and DAQ for the 50 kton ICAL detector.

A detector on the scale of ICAL has never been built in the country before. It is therefore prudent to build a smaller version and gain experience with the various subsystems and make course corrections on the way towards the design and fabrication of the 50 kton detector. The INO collaboration decided to build a 1 m^3 ICAL prototype detector and install it at VECC, Kolkata. This detector will track cosmic muons, which are plentiful overground (∼200 m^{-2} sec^{-1}). The overall size of the magnet will be ∼2.5 m × 2.3 m × 1.3 m. A schematic is shown in Fig. 6.

Figure 5. Stack of twelve 1 m^2 glass RPC at TIFR.

Figure 6. The prototype magnet at VECC, Kolkata.

The simulation of the 50 kton ICAL has been done in 3 steps viz. defining the detector geometry, generating events using the neutrino event generator, NUANCE, [**?**] and projecting the data in a form suitable for visualization and analysis. In the third step a user program uses the simulated data, suitably digitized, and reconstructs particle tracks, their energy-momentum using the track curvature in the magnetic field and, if possible, identifies the particle. More details may be found in Ref. [4].

Finally an update on the INO initiative to develop expertise among the younger group of people who will be associated with the INO project for the next 10 years or more. This will also provide a strong base for future high energy projects, both national and international. A modest beginning was made in 2007 and in August, 2008 the INO Ph.D. program began at TIFR, Mumbai with the first batch of 5 students.

A draft of the design report for the mechanical structure and assembly of the ICAL magnet and the ancillary mechanical facilities is ready and under review. The detailed project report (DPR) for the site and associated infrastructure, including that necessary for the underground and overground laboratories, has been commissioned by an Engineering Task Force of the Dept. of Atomic Energy, India and prepared by the TNEB (Tamilnadu Electricity Board), India. A report on the Environment Management Plan was commissioned by the INO collaboration and prepared by Care Earth, Chennai. This was especially necessary as the underground site for INO lies in the Nilgiri Biosphere and is close to the Mudumalai Wildlife Sanctuary. The Ministry of Environment has given the go-ahead to the Project pending clearance by the Ministry of Forests, Govt of Tamilnadu which is awaited.

An approximate timeline is that the first phase, involving the setting up of the 50 kton detector, should be completed 8 years from the time of financial sanction. By then other experiments such as Double-CHOOZ and Daya-Bay would have measured or put an upper limit on θ_{13}. If this parameter, which is crucial to the existence of matter effects that would be measurable by ICAL, is not too small the next phase of adding additional modules totalling 50 kton would be undertaken. The construction time should be smaller for the second phase, perhaps $\sim$ 3 - 4 years. Efforts are also being made to seek international participation in this experiment. If such collaborations materialise (also with accelerator based groups) the possibility of doing long baseline neutrino measurements, with much higher sensitivity to some of the neutrino parameters, might become a reality.

It may be mentioned that INO, an approved project of the Government of India, will be jointly funded by the Department of Atomic Energy and the Department of Science & Technology. The total projected cost, as of now, is Rs. 920 crores (∼$ 200 million) over two Plan periods. About a third of this estimated budget is for the low carbon steel for the 50 kton magnet.

4. Summary and outlook

The R&D effort of the INO collaboration has been focused on the ICAL has been reasonably successful. It looks forward to formal financial sanction by the Govt. of India by the end of 2008. In view of this we seek and welcome collaboration with groups from the international community of neutrino physicists.

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