THE INDIA BASED NEUTRINO OBSERVATORY - PRESENT STATUS

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Abstract

The current status of the India based Neutrino Observatory (INO) is summarized. The two major physics goals are (a) unambiguous demonstration of neutrino oscillation and a more precise measurement of the associated neutrino parameters and (b) to search for matter effects in neutrino oscillation, using the charge identification capability of the magnetized iron calorimeter, which would help determine the sign of one pair of neutrino mass differences. The status of the 1 m^3 prototype iron calorimetric detector, the design of the 50 kton magnet, the experience with resistive plate chambers used for tracking the charged particles produced in neutrino-iron interactions and the planned electronics and data acquisition system will be presented.

INTRODUCTION

The neutrino was invented by Pauli [1] in 1930 to resolve the energy-momentum conservation and spin-statistics crisis in beta decay. The first evidence of the existence of the electron (anti)neutrino was provided in a pioneering reactor experiment [2]. This was followed by the discovery of the muon neutrino and, much later, the tau neutrino [3]. The helicity of the neutrino was shown [4] to be -1 $\pm$ 0.3 in agreement with the two component neutrino theory. An upper limit of the anti-neutrino mass was set at about 55 eV/c^2 through a careful measurement of the beta spectrum in tritium decay near the end point [5]. After unsuccessfully searching for neutrinos at a reactor (which is a copious source of *anti*neutrinos) [6] Davis used the radiochemical detection technique, involving the separation of ^{37}Ar from 600 tons of the cleaning fluid C_2Cl_4 containing ^{37}Cl, to measure neutrinos produced in nuclear reactions, and beta decays of the unstable nuclei produced thereby, in the hot core of the sun [7]. The roughly threefold shortage came to be known as the solar neutrino problem [8]. One of the explanations proposed to explain this shortfall was that the electron neutrinos produced in the solar interior change into another type (flavour) of neutrino, which is not measurable by the ^{37}Cl based detector. This chameleon like behaviour, known as neutrino oscillation, was first proposed by Pontecorvo [9]. The solar neutrino problem was resolved in a definitive manner by the Sudbury Neutrino Observatory experiment [10] using 1 kton of heavy water. Charged current interactions measured the electron neutrinos while neutral current events measured all neutrinos, irrespective of their type or flavour (ν_e, ν_μ, ν_τ). The shortfall in the ν_e flux was recovered in the flux of $\nu_\mu + \nu_\tau$.

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Table 1: Best values of neutrino parameters.

Parameter	Exp. value (1σ)
Δ^2_{21}	(7.9$\pm$0.4)$\times10^{-5}$ eV^2
Δ^2_{23}	$\pm$2.4$\pm$0.2$\times10^{-3}$ eV^2
θ_{12}	$34.1^\circ\,^{+1.6^\circ}_{-1.2^\circ}$
θ_{23}	$41.6^\circ\,^{+5.7^\circ}_{-2.9^\circ}$
θ_{13}	$<8^\circ$

An equally intriguing problem resulted from the detailed measurements of atmospheric neutrinos. The IMB [11] and Kamiokande [12] collaborations found an anomalous ν_μ/ν_e ratio as a function of zenith angle. This ratio is expected to be close to 2, for high energy neutrinos, and the same for all directions in the absence of oscillations. If ν_μ oscillates into ν_τ the above ratio would be 2 for down going neutrinos but smaller than 2 for upgoing neutrinos. SuperKamiokande provided the first definitive results [13] which showed that neutrinos oscillate and therefore possess a small mass. It may be mentioned that atmospheric neutrinos were first detected at Kolar Gold Fields by an Indian team, just ahead of an experiment led by Reines in a South African mine [14].

The above mentioned, as well as a few more, key experiments have led to a dramatic change in our understanding of neutrinos and cannot be understood within the hitherto successful standard model of high energy physics. The widely accepted explanation of the experimental observations is that neutrinos switch identities, or oscillate into other flavours, as they propagate. This can occur if the flavour eigenstates (electron, muon and tau) are not simultaneously mass eigenstates (m_1, m_2, m_3). In general these two bases are connected by a unitary matrix. For 3 active flavours there are 7 independent parameters *viz.* the 3 mass parameters, 3 mixing angles θ_{12}, θ_{13}, θ_{23} and δ_{CP}. If the neutrino is its own (Majorana) antiparticle there are two additional phases which, however, would not be observable in ν-oscillation experiments. Table 1 lists the presently known experimental values [15]. Here Δm^2_{ij} is defined as m^2_i-m^2_j.

There are several experiments planned in the near future which will improve the precision further and might even throw up unexpected results. Neutrinos are providing us the first clues to physics beyond the standard model and their study is expected to provide even more surprises. With a view of reentering this exciting area an initiative has been taken to set up an underground laboratory in India. One of the main experiments is aimed at making precision measurements on atmospheric neutrinos using a large iron calorimetric (ICAL) detector.

Two other important problems in neutrino physics should be mentioned. The first of these is that we do not yet know whether the neutrino is its own antiparticle (Majorana) or not (Dirac). A definitive measurement confirming or disproving the claim [16] of observing neutrinoless double beta decay (DBD) (which, if true, makes the neutrino a Majorana particle) would be crucial. Moreover, if the neutrino is a Majorana particle, the rate of 0ν DBD can be related to its absolute mass. The second important problem is to measure the absolute mass of the neutrino irrespective of whether it is a Majorana or Dirac particle. Presently the upper limit derived from a beta spectral measurement of tritium is 2.2 eV/c^2 [17] and there are plans to search for a mass down to about 0.2 eV/c^2 [18].

MAJOR PHYSICS GOALS OF ICAL

The major physics issues and questions that the ICAL detector will address are: (1) Observation of oscillatory pattern 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}. This depends crucially on the magnitude of θ_{13} which will be determined by other ongoing/planned experiments. (3) Whether θ_{23} is 45°; else determine whether $<$ or $>$45° (octant ambiguity). (4) Measure leptonic CP phase δ_{CP}, if θ_{13} is non-zero. Item no.2 can be studied using atmospheric neutrinos provided θ_{13} is $>$ about 5°. The sensitivity to the ordering of the neutrino masses arises as follows. The $\nu_\mu - \nu_\tau$ and $\nu_\tau - \nu_e$ mixing changes, through the $\nu_e - e$ charged current interaction, both the mass and the mixing angle from their vacuum values to those in the presence of matter. The sign of the contribution to each of these is opposite for neutrino and antineutrino for a given Δ_{32}. For the opposite sign of Δ_{32} these contributions change sign allowing a discrimination between the the normal (Δm^2_{32} >0) and inverted (Δm^2_{32} <0) hierarchies. At a later stage this and items 3 and 4 could be studied even better with an accelerator produced neutrino beam and neutrino factory, respectively.

CHOICE OF DETECTOR AND SITE

The ideal neutrino detector should have as low a threshold as possible possibly sub-MeV if it should be sensitive to geo, nuclear reactor, solar, supernovae and atmospheric neutrinos. Keeping in mind the physics reach of a potential detector, the technical capability of our R&D and that of our industry, feasibility of fabrication and assembly of subsystems of the detector and the time required to make it while being competitive internationally, a large magnetized iron calorimeter (ICAL) 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 that threshold. While the choice of 6 cm 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 [19] 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 charged current interaction of ν_μ and $\bar{\nu}_\mu$, respectively, was stressed in a recent APS study [20]. 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[21].

A magnetized iron calorimeter is an attractive option if charge identification of the muons following a charged current interaction with the target nucleus is necessary. A magnetic field of about a 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. It is available in large quantities and is reasonably cheap.

A reasonably precise measurement of the energy-momentum of the interacting atmospheric neutrino is required to measure L/E on an event by event basis. This can be done through by tracking the charged muon, produced via the charged current neutrino-nucleus interaction, by 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 detectors. 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. The R&D work on the glass RPC detector including the associated subsystems involving gas circulation, electronics and data acquisition is ongoing.

In consultation with the Geological Survey of India two possible sites for INO were identified, one at Rammam near Darjeeling in West Bengal and another at PUSHEP, Masinagudi, near the foothills of the Nilgiris in Tamilnadu. Two teams made an in depth study of the advantages and shortcomings of each site. A site selection committee consisting of physicists, a civil engineer and geologists was formed. Criteria were framed to decide the suitability in terms of depth, seismicity, proximity to industrial centres, access by road etc. This committee looked into all aspects and recommended, unanimously, that Masinagudi was the preferred site for INO.

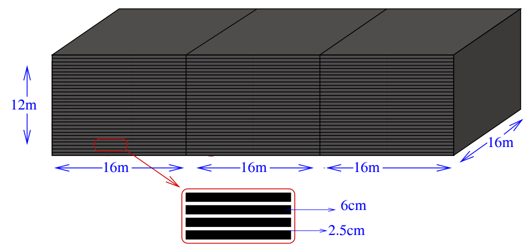

Figure 1: Schematic view of the 50 kton iron calorimeter detector consisting of 3 modules each having 140 layers of iron plates.

ICAL AND SUBSYSTEMS

The conceptual design of ICAL has been made and has a modular structure. Each module weighing 16 kton has a size of 16 m$\times$16 m$\times$12 m 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 tesla. A schematic of the 50 kton detector is shown in Fig. 1.

Some more details of each of the subsystems including the present status are given in the following sections.

Magnet

The main design criteria for the ICAL magnet were piecewise field uniformity, modularity, optimum copper-to-steel ratio and access for maintenance. A preliminary design of the 16 kton module has been made including a finite element calculation of the magnetic field, using the commercial software Magnet 6.0 [22], for a few configurations of the current carrying coils. Based on these calculations the presently preferred configuration was arrived at. More details may be found in Ref.[23].

Resistive plate chamber

The resistive plate chamber consisting of two glass plates 2 m$\times$2 m area and 2 mm thick separated by an insulating spacer of 2 mm will be used. This choice of glass, as opposed to bakelite, was based on considerations such as cost, availability, ease of construction and suitability for an underground experiment involving low event rates. Most of the R&D work has been carried out using RPCs 30 cm$\times$30 cm in size but a few chambers of a larger size (1.2 m$\times$0.9 m) have also been made. 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. 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 identified.

A test stack with 10 small sized RPCs (30 cm$\times$30 cm) was set up at the RPC laboratory at TIFR and used to track cosmic muons. The trigger was provided by plastic strip scintillator detectors placed above and below the RPC stack. Fig. 2 shows a picture of the setup. The RPCs have been operated in the streamer mode, with a gas mixture of HF134a:Ar:isobutane of 62:30:8, or in the avalanche mode with HF134a:isobutane of 95.5:4.5. The electronic pulse following a minimum ionizing particle traversing the RPC is a few hundred mV across a 50Ω load when operated in the streamer mode, while the corresponding figure for the avalanche mode is between 1-5 mV. While the streamer mode of operation simplifies the electronics, since the pulse can directly trigger a fast timing discriminator, the counters have not functioned in this mode for periods beyond about a month. The reason could be the formation of HF in the presence of moisture as an impurity in the detector gas. On the other hand two RPCs have been operating with individual efficiencies of 75-85% in the avalanche mode for a period of more than 1 year. Both these counters have dimensions of about 30 cm$\times$40 cm and have been made from Japanese float glass. The problem of short lifetimes of RPCs [24] using local float glass could be because of some critical parameters and is being addressed through measurements of chemical composition, surface roughness as probed by reflectivity and atomic force microscopy etc.

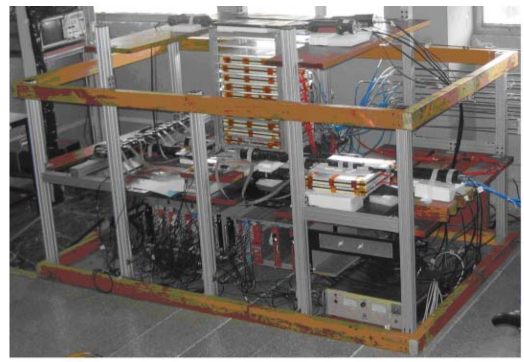

Figure 2: Muon tracking setup using RPC stack.

Gas mixing and distribution system

A 4-gas mixing and distribution unit suitable for the test bench as well as for the prototype 1 m^3 detector was designed and developed locally (see Fig. 3). It can supply gas at slightly above 1 bar to 16 detectors and can be operated in a continuous flow mode. The important features of this system are an input gas purifier (to remove oil and moisture traces) and 2 μm dust filters, a gas mixing system using mass flow controllers, flow sensors and monitors, moisture monitor, safety bubblers on individual gas lines to prevent excess-pressure in the RPCs, isolation bubblers using low vapour pressure silicone oil preventing air, into which the gas is vented, from back diffusing into the RPC, an exhaust manifold and a remote control and monitoring system with a PC interface.

Figure 3: Front view of the 4-component gas mixing unit with 16 output channels.

The designing of a closed loop gas system for the 50 kton detector has been initiated. The system would be capable of mixing upto 4 gases, have a purification column to remove trace amounts of moisture and detector gas breakdown products, gas manifolds, flow controllers (mass flow controllers and impedances), sensors for measurement of various gas parameters such as flow, temperature, pressure, humidity etc and their logging in PC based readout and acquisition system.

Electronics and data acquisition system

The passage of a minimum ionizing particle induces a voltage pulse on the corresponding X- and Y- pickup strips. This pulse (with or without amplification, depending on whether the RPC is operated in the avalanche or streamer modes) goes to a fast timing discriminator (TD) located at the end of the strip. The logic output of the TD is then used to tag the strip which was 'hit' and also given to a multiplexed TDC for recording the time information. An FPGA based trigger module fabricated in-house recording the hit pattern and multiplexing will be used in the prototype detector tests. A multi-level programmable trigger generator with physics motivated trigger logic will be used to initiate data recording. The data acquisition system (DAQ) will be based on the VME standard and will be linked to PCs with the Linux OS. More details may be found in the Ref.[23]. The present plan is to use a scaled up version of this system but experience with the 1 m^3 prototype detector should provide inputs for the ICAL detector electronics and DAQ.

ICAL prototype

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 $\sim$2.6 m $\times$ 2.8 m $\times$ 2.5 m ICAL prototype detector. This detector will track cosmic ray muons.

SIMULATION OF ICAL

The simulation of the 50 kton ICAL has been done in 3 steps. Firstly, the detector geometry was defined using the GEANT [25] detector simulation software from the CERN library. Neutrino events were generated using NUANCE [26]. Finally the simulated data was used to reconstruct particle tracks and their energy-momentum. The data can now be projected for analysis and visualization. A sample plot is shown in Fig. 4 which compares the allowed region in θ_{23}-Δm^2_{23} space from ICAL simulations with SK results [27].

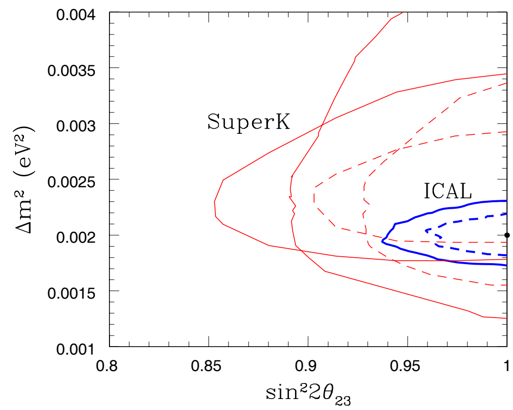

Figure 4: Allowed parameter space from a 300 kton.yr ICAL simulation using fully contained CC muon events (dashed-90% CL, full-99%CL) compared with SK results. The input parameters used in the simulation are indicated by the dot in the figure.

TRAINING PEOPLE FOR INO

There is a need 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. Various ideas are discussed in the INO Project report such as the formation of an INO School modelled on the lines of the successful BARC Training School, direct recruitment of physicists and engineers and instituting INO Fellowships at selected universities, engineering colleges, NIITs and IITs. A modest beginning in the first mentioned approach has been made this year. A 4 week intensive program involving about a dozen students and recently recruited staff (with a physics background) doing INO related work at the various centres was completed in April-May of 2006. The theoretical component was organized and conducted by HRI, Allahabad while the experimental portion took place at VECC, Kolkata. The feedback was good and hence encouraging.

ESTIMATED COST AND TIME

The INO project has been put up through the Mega-sciences Committee of the Department of Atomic Energy for the 11th five-year plan. The INO project report [23] has most of the details as of May 2006. The total projected cost is Rs. 670 crores over 2 plan periods. About half of this estimated budget is for the low carbon steel for the 100 kton magnet.

The detailed project report (DPR) for the site and associated infrastructure, including that necessary for the underground and overground laboratories, is being prepared by the TNEB (Tamilnadu Electricity Board) engineering team. This contract was given by an Engineering Task Force set by Chairman, DAE. This DPR is expected to be ready by the end of the 10th plan period. A similar DPR will be prepared by a team of scientists and engineers for the ICAL.

An approximate timeline is that the first phase, involving the setting up of the 50 kton detector, should be completed 5 years from the time of financial sanction. By then other experiments such as double-CHOOZ 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 years. Efforts are also being made to seek international participation in this experiment. If such collaborations materialize 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.

PRESENT STATUS OF INO

An interim report of the INO project was presented in May 2005 to the Chairman, DAE. Another presentation was made to the Scientific Advisory Committee to the Prime Minister in September, 2005. It was well received and a specific suggestion made to get it peer reviewed by international experts. The report was sent to seven distinguished scientists including six internationally well known experts in neutrino physics and one from India. The reports are generally very positive. Most referees have urged speedy construction in view of potential competition and another has expressed concern about the availability of adequate human resources. In any case, the collaboration is seeking a stronger participation, both national and international. The INO project is also one of the two mega-projects identified by the high energy physics community in the DAE-DST Roadmap meeting for high energy, nuclear and astro-physics held in April, 2006 at HBCSE, Mumbai. The INO collaboration looks forward to formal financial sanction by the Planning Commission and the Govt. of India by the 2nd half of next year.

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