The India based Neutrino Observatory - present status

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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 [3] and, much later, the tau neutrino [4]. The helicity of the neutrino was shown [5] to be -1 ± 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 [6]. After unsuccessfully searching for neutrinos at a reactor (which is a copious source of antineutrinos) [7] Davis used the radiochemical detection technique, involving the separation of $^{37}$Ar from 600 tons of the cleaning fluid C$_2$Cl$_4$ 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 [8]. The roughly threefold shortage came to be known as the solar neutrino problem [9]. 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 [10]. The solar neutrino problem was resolved in a definitive manner by the Sudbury Neutrino Observatory experiment [11] using 1 kton of heavy water. Charged current(CC) interactions measured the electron neutrinos while neutral current events measured all neutrinos, irrespective of their flavour ($\nu_e, \nu_\mu, \nu_\tau$). The shortfall in the $\nu_e$ flux was recovered in the flux of $\nu_\mu + \nu_\tau$.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Exp. value (1$\sigma$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta^2_{21}$</td>
<td>(7.9±0.4)×10$^{-5}$ eV$^2$</td>
</tr>
<tr>
<td>$\Delta^2_{23}$</td>
<td>(±2.4±0.2)×10$^{-3}$ eV$^2$</td>
</tr>
<tr>
<td>$\theta_{12}$</td>
<td>34.1$^{+2.2}_{-1.5}$$^\circ$</td>
</tr>
<tr>
<td>$\theta_{23}$</td>
<td>41.6$^{+4.9}_{-3.4}$$^\circ$</td>
</tr>
<tr>
<td>$\theta_{13}$</td>
<td>&lt;8$^\circ$</td>
</tr>
</tbody>
</table>

An equally intriguing problem resulted from the detailed measurements of atmospheric neutrinos. The IMB [12] and Kamiokande [13] collaborations found an anomalous $\nu_\mu/\nu_\tau$ 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 $\nu_\mu$ oscillates into $\nu_\tau$ the above ratio would be 2 for down going neutrinos but smaller than 2 for upgoing neutrinos. SuperKamiokande(SK) provided the first definitive results [14] 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 [15], just ahead of another led by Reines in a South African mine [16].

These and other [17] 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 is that neutrinos switch identities, or oscillate within the hitherto successful standard model of neutrinos and cannot be understood.

The major physics goals of ICAL

The major physics issues and questions that the ICAL detector 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. Item no. 2 can be studied using atmospheric neutrinos provided \(\theta_{13}\) is > about 5\(^\circ\). The sensitivity to the ordering of the neutrino masses arises as follows. The \(\nu_\mu - \nu_\tau\) and \(\nu_\tau - \nu_\mu\) mixing changes, through the \(\nu_\tau - e\) charged current interaction, both the mass and the mixing angle from their vacuum values to those in the presence of matter. The contribution to each of these switches sign for neutrino and antineutrino (for a given \(\Delta m^2\) and with the sign of \(\Delta m^2\)). For the opposite sign of \(\Delta m^2\) these contributions change sign allowing a discrimination between the the normal (\(\Delta m^2 > 0\)) and inverted (\(\Delta m^2 < 0\)) hierarchies. The \(\nu_\mu \rightarrow \nu_\tau\), \(\nu_\mu \rightarrow \nu_\tau\) appearance and \(\nu_\mu \rightarrow \nu_e\) survival probabilities are shown in Fig. 1 at a certain propagation distance in vacuum and including the matter effect for both the 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.

![Graph showing appearance and survival probabilities for neutrino transitions](image)

**FIG. 1:** Appearance and survival probabilities for $\nu_e$, $\nu_\tau$ and $\nu_\mu$ vs $E_\nu$ (GeV) for muon neutrinos at 2 distances in vacuum and in matter for the two signs of $\Delta_{32}$.

**Choice of detector and site**

The ideal neutrino detector should have an energy threshold of $\sim$100 keV if it should be sensitive to geo, nuclear reactor, solar, supernovae and atmospheric neutrinos (see Appendix for a list of various neutrino sources, some typical neutrino cross sections and detector sizes for reasonable count rate). 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 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. While 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 [22] 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 $\mu^+$ and $\mu^-$ produced through CC interactions of $\nu_\mu$ and $\bar{\nu}_\mu$, respectively, was stressed in a recent APS study [23]. 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 [24].

The iron in ICAL serves two purposes viz. providing target atoms for $\nu$ interactions and supporting a sufficiently strong magnetic field to bend energetic muons produced in these interactions. 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 derive the matter propagation length, and hence $L/E_{\nu}$, on an event by event basis. This can be done by tracking the charged muon, produced via the charged current neutrino-nucleus interaction, by many layers of a position sensitive detector even if it does not stop in ICAL. The directional information, up or down going, can be obtained for muons 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 an appropriate 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.
Magnet and their present status are given below.

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.

The conceptual design of ICAL has been made and has a modular structure. Each 16 kton module has a size of 16 m×16 m×12 m and 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 ~1 tesla. Further cooling, if required, can be done by a forced air draft.

The mechanical and electrical specifications of the magnet and the coil are given in Table II. In the present design a solid copper conductor is used whose cooling is by conduction through the iron plates and by radiation from the iron surface. Estimates of cooling due to conduction and radiation suggest that the rise in temperature is within a few degrees Celsius. Further cooling, if required, can be done by a forced air draft.

A 100-fold scaled down version of the ICAL module has been fabricated with only 2 layers of soft iron at VECC, Kolkata. The field was measured, in a specially prepared slot, using a Hall probe and agreed well with the simulation.

**Resistive plate chamber**

The resistive plate chamber consisting of two glass plates 2 m×2 m area and 2 mm thick separated by an insulating spacer of 2 mm will

![Fig. 2: Schematic view of the 50 kton iron calorimeter detector consisting of 3 modules each having 140 layers of iron plates.](image)

![Fig. 3: Schematic of 16 kton ICAL module.](image)
FIG. 4: Field lines in a horizontal (x-y) plane of any of the iron plates, the arrows denote the field direction.

**TABLE II: Specifications of the magnet steel and the coil for one module**

<table>
<thead>
<tr>
<th>STEEL</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>16 m</td>
</tr>
<tr>
<td>Width</td>
<td>16 m</td>
</tr>
<tr>
<td>Height</td>
<td>11.9 m</td>
</tr>
<tr>
<td>Plate thickness</td>
<td>6.3 cm</td>
</tr>
<tr>
<td>No. of plates</td>
<td>135</td>
</tr>
<tr>
<td>Steel specification</td>
<td>ASE 1010 or C10</td>
</tr>
<tr>
<td>Carbon content</td>
<td>0.1%</td>
</tr>
<tr>
<td>Weight of steel</td>
<td>51,000 ton</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>COIL</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Coil dimension</td>
<td>20 cm × 100 cm</td>
</tr>
<tr>
<td>Coil height</td>
<td>15 m</td>
</tr>
<tr>
<td>Coil weight</td>
<td>82 ton</td>
</tr>
<tr>
<td>Copper cost @ Rs.400/kg</td>
<td>Rs.7.5 crore</td>
</tr>
<tr>
<td>Amp-turns</td>
<td>40,000</td>
</tr>
<tr>
<td>No. of turns</td>
<td>20 × 100 × 2</td>
</tr>
<tr>
<td>Conductor size</td>
<td>1 cm × 1 cm</td>
</tr>
<tr>
<td>Current</td>
<td>10 A</td>
</tr>
<tr>
<td>Resistance</td>
<td>15.6 Ω</td>
</tr>
<tr>
<td>Voltage</td>
<td>156 Volt</td>
</tr>
<tr>
<td>Power dissipation</td>
<td>3.1 kW</td>
</tr>
<tr>
<td>Coil inductance</td>
<td>1710 Henry</td>
</tr>
<tr>
<td>Rise in coil temp.</td>
<td>≤ 4°C</td>
</tr>
<tr>
<td>Rise in iron temp.</td>
<td>≤ 2°C</td>
</tr>
<tr>
<td>Stored magnetic energy</td>
<td>5.3 MJ</td>
</tr>
<tr>
<td>Characteristic</td>
<td>~ 110 s</td>
</tr>
<tr>
<td>mag. time (L/R)</td>
<td></td>
</tr>
</tbody>
</table>

be used. A schematic of the RPC is shown in Fig. 5. 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 × 30 cm in size but a few chambers of a larger size (1.2 m × 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. It will be necessary to identify and then work together with local industry for perfecting various industrial processes needed in the manufacture of reliable and rugged RPCs.

A test stack with 10 small sized RPCs (30 cm × 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. 6 shows a picture of the setup and Fig. 7 shows typical muon tracks visualized on a PC monitor.

The RPCs have been operated in the streamer mode, with a gas mixture of HF134a:Ar:isobutane of 62:30:8, or in the
FIG. 6: Muon tracking setup using RPC stack.

FIG. 7: Some interesting tracks recorded in the detector.

average 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 × 40 cm and have been made from Japanese float glass. The problem of short lifetimes of RPCs [26] 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. Other options such as using a freon-less detector gas are also being explored.

Gas mixing and distribution system

A 4-gas mixing and distribution unit suitable for the test bench as well as for the prototype 1 m³ detector was designed and developed locally (see Fig. 8). 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.

The designing of a closed loop gas system for the 50 kton detector has been initiated. The system would be capable of mixing up to 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) after impedance matching 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 digitizing the time. 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 Linux based PCs (for more details see Ref.[27]). 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 1 m$^3$ ICAL prototype detector and install it at VECC, Kolkata. This detector will track cosmic muons, which are plentiful overground ($\sim$200 m$^{-2}$ sec$^{-1}$). The overall size of the magnet will be $\sim$2.6 m $\times$ 2.8 m $\times$ 2.5 m. A schematic is shown in Fig. 9.

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 [28] detector simulation software from the CERN library. This program also tracks particles produced in the neutrino interactions with the detector material including energy losses by ionization and also energetic secondaries, if any. The second important component is the neutrino event generator NUANCE [29]. This program provides a choice of neutrino fluxes as also three-flavour neutrino mixing. In the third step a user program takes 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. Finally the data is projected in the form suitable for visualization and analysis. A sample plot is shown in Fig. 10 which compares the allowed region in $\theta_{23}$-$\Delta m_{23}^2$ space from ICAL simulations, using only fully contained CC events and a 300 kton.yr exposure, with the corresponding re-
FIG. 10: 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 are indicated by the dot.

A small beginning towards training people - the first INO school

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, NI-ITs 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 positive and hence quite encouraging.

Estimated cost and time schedule

The INO project has been put up through the Megasciences Committee of the Department of Atomic Energy for the 11th five-year plan. The INO project report [27] 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 50 kton magnet.

The detailed project report (DPR) for the site and associated infrastructure, including that necessary for the underground and over-ground 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 $\theta_{13}$. 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 updated 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 was 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.

Appendix - Neutrino sources, fluxes, cross sections and detector size

A list of neutrino sources along with the relevant decay/reaction that produced them, the approximate range of energy, flux and interaction cross section (CC) is given in the Table III below. Solar neutrinos are produced via the pp chain. The first of these reactions produces the largest number of low energy neutrinos. The high energy neutrinos which are much less numerous are primarily from the beta decay of $^{8}$B.

Atmospheric neutrinos are produced in cosmic ray interactions with the upper atmosphere. The charged pions produced in these interactions undergo weak decay via $\pi^{+} \rightarrow \mu^{+} + \nu_{\mu}$ (and the conjugate process for the $\pi^{-}$). The muon produced thereby also decays via $\mu^{+} \rightarrow e^{+} + \nu_{e} + \bar{\nu}_{\mu}$ (and the conjugate process for the $\mu^{-}$). Thus for every electron neutrino there are two muon neutrinos. The neutrino flux is nearly isotropic for energies beyond $\sim 1$ GeV and the energy spectrum may be found in [27].

Neutrinos from man made sources such as nuclear power reactors have been used in the CHOOZ and Kamland experiments and are central to the planned double-CHOOZ and Daya Bay experiments.

Geo-neutrinos arise mainly from beta decays of daughter beta emitters in the uranium and thorium decay chains and the naturally occurring $^{40}$K. Natural radioactivity accounts for $\sim 40\%$ of the amount of outward heat flux from the earth.

Supernova explosions occur when a star has used up its nuclear fuel and collapses under its own gravitational force. Supernovae are prolific sources of neutrinos of all flavours. Almost 99% of the total energy released ($\sim 3 \times 10^{53}$ ergs for SN1987a) is in the form of 10-100 MeV neutrinos in a few seconds.

The large size of a typical neutrino detector is dictated by the tiny $\nu$-nucleus interaction cross section. For the case of atmospheric neutrinos incident on iron, the mean free path $\lambda=1/(n\sigma)$ is $\sim 1.2 \times 10^{13}$ m. For a total counts of $10^3$/year or about 3/day, the detector volume is $\sim 15000$ m$^3$ implying a size of $\sim 25$ m.

References

TABLE III: Neutrino sources and approximate fluxes.

<table>
<thead>
<tr>
<th>Source</th>
<th>Reaction</th>
<th>Energy (approx.)</th>
<th>Approximate flux (m(^{-2})sec(^{-1}))</th>
<th>Cross section (cm(^2))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar reactor</td>
<td>p(p,d)e(^+)(\nu_e)</td>
<td>0.1 MeV</td>
<td>(6 \times 10^{14})</td>
<td>(\nu_e)Ga (10^{-45})</td>
</tr>
<tr>
<td>Solar reactor</td>
<td>(^8)B(\rightarrow)(^7)Be e(^+)(\nu_e)</td>
<td>0.1-15 MeV</td>
<td>(6 \times 10^{10})</td>
<td>(\nu_{\mu},\nu_{\tau}) 10(^{-43})</td>
</tr>
<tr>
<td>Atmospheric</td>
<td>p(\rightarrow)(\mu)(\nu_\mu), (\mu)(\rightarrow)e(\nu_e)</td>
<td>0.1-10 GeV</td>
<td>(10^{10})</td>
<td>(\nu_e)N (10^{-38})</td>
</tr>
<tr>
<td>Supernova</td>
<td>p+e(\rightarrow)n+(\nu_e), e(^+)e(^-)(\rightarrow)(\nu_\mu)+(\nu_\tau)</td>
<td>0.1-10 MeV</td>
<td>(10^{15}) (\sim)1 km from 1GW(\nu)</td>
<td>(\nu_e)p (10^{-43})</td>
</tr>
<tr>
<td>Nucl radioactivity</td>
<td>U,Th daughters, (^{40})K</td>
<td>0-3.3 MeV</td>
<td>(10^{12}) for SN1987a</td>
<td>(10^{-44})</td>
</tr>
</tbody>
</table>


[18] GEANT - Detector Description and Simulation Tool, CERN Program Library W5013 (http://wwwasd.web.cern.ch/~geant/).


[28] GEANT - Detector Description and Simulation Tool, CERN Program Library W5013 (http://wwwasd.web.cern.ch/~geant/).


[34] D.A. Petyt, for the MINOS-NuMI Collaboration, Joint Experimental/Theoretical Physics seminar at Fermi Lab, 30 March 2006. See http://www-umni.fnal.gov/talks/results06.html.

[35] Magnet 6.0 finite element electromagnet software from Infolytica, Canada.


[38] GEANT - Detector Description and Simulation Tool, CERN Program Library W5013 (http://wwwasd.web.cern.ch/~geant/).
