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Discussion on a possible neutrino detector located in India

Coordinators : M. V. N. MURTHY[1] and U. A. YAJNIK[7]

Participants and contributing authors: K.R.S. Balaji (1), G. Bhattacharyya (2), Amol Dighe (3), Shashikant Dugad (4), N.D. Hari Dass (1), P.K. Kabir (5), Kamales Kar (2), D. Indumathi (1), John G. Learned (6), Debasish Majumdar (2), N.K. Mondal (4), M.V.N. Murthy (1), S.N. Nayak (7), Sandip Pakvasa (6), Amitava Raychaudhuri (8), R.S. Raghavan (9), G. Rajasekaran (1), R. Ramachandran (1), Alak K. Ray (4), Asim K. Ray (10), Saurabh Rindani (11), H.S. Sharatchandra (1), Rahul Sinha (1), Nita Sinha (1), S. Umasankar (7), Urjit A. Yajnik (7)

(1) IMSc, Chennai (2) SINP, Calcutta (3) CERN, Geneva (4) TIFR, Mumbai (5) U. Virginia, Charlottesville (6) U. Hawaii, Honolulu (7) IIT Bombay, Mumbai (8) U. Calcutta, Calcutta (9) Bell Labs, Lucent Tech, Murray Hill (10) Viswa Bharati, Santiniketan (11) PRL, Ahmedabad

Abstract. We have identified some important and worthwhile physics opportunitites with a possible neutrino detector located in India. Particular emphasis is placed on the geographical advantage with a stress on the complimentary aspects with respect to other neutrino detectors already in operation.

1. Motivation

- The possibility of a Neutrino Observatory located in India was discussed as early as 1989 during several meetings held that year. Since then this question has come up in many private discussions off and on. The issue was raised again in the first meeting of the Neutrino physics and Cosmology working group during WHEPP-6 and it was decided then to collate concrete ideas for such a detector.

- Historically, the Indian initiative in Cosmic Ray and Neutrino physics experiments goes back nearly 45 years. In fact the first atmospheric neutrino induced muon events were recorded at the KGF underground laboratory nearly thirty five years back. While Cosmic Ray experiments are still continuing, Indian neutrino physics has taken a beating due to the closure of one of the best locations, Kolar Gold Mines, for such experiments. It appears that a resurrection is possible only if there are alternative locations available.

- The biggest advantage in such a detector is the geographical location. Most of the neutrino detectors are scattered around the world at latitudes above 35°. There is none close to the equator as yet. It is possible to push such a detector (henceforth called INO) down to almost 8° latitude if a convenient location is available. Equatorial location permits solar neutrino oscillation studies through the earth's core, possible studies of the core density, and permits doing neutrino astronomy searches covering the whole celestial sky.

- The working group concentrated on generating physics ideas for such an initiative without necessarily specifying what type of detector is necessary for studying the physics. However, parallel discussions also took place on some specific configurations guided by the physics discussions. The major motivation behind this exercise is then to detail all the relevant physics ideas, and then to view them in juxtaposition with the available experimental resources and expertise. Having thus highlighted the possible goals of such an Indian Neutrino Observatory, it may then become easier to home-in on one or more suitable experiments, both in the long-term and in the short-term, which can be carried on there.

- An important aspect of INO should also be that not only should it have new physics ideas, it should be complementary to the other detectors which are already running, or will be on-line soon. Such a world class facility is naturally expected to attract worldwide attention as well as participation. It may also have continuous operations such as background measurements of various kinds which, while not being fashionable, will also help in realising front line and secondary physics objectives.

2. Physics Goals

This is best studied by considering different aspects of neutrino physics separately. All these ideas may not be incorporated in a single detector. Rather this is more like a wish list.

2.1 Solar neutrino physics

The current and planned solar neutrino detectors are all at latitudes above 35 degrees. These detectors have very small exposure times to neutrinos traveling through the core of the earth, about ten days in a year. The MSW phenomenon can play an important role in the regeneration of neutrinos in earth's core. To study this, it is important to build a solar neutrino detector as close to the equator as possible. India offers a possibility geographically, as well as in terms of scientific expertise, engineering expertise, manufacturing, and tall mountains which provide good shielding.

Such a detector will allow one to check the parameter range for time-of-night variation. Some effort is needed to examine the theoretical issues involved more closely. For example, there is a need to do a detailed calculation of rates, for a hypothetical detector located close to the equator, taking into account the constraints on the neutrino parameters already in existence. This effort is needed to examine the basis of justification of such a large endeavour, but preliminary indications at this workshop make it appear promising.

While many aspects of solar neutrinos will have been well investigated by the time an Indian effort can be mounted, there are some further areas which will remain uninvestigated. An example would be the measurement of the higher energy tail of the solar neutrinos, in the range of 13-17 MeV where Hep neutrinos can be measured, and where SuperK, the presently largest instrument planned, will not have accumulated good statistics. Typical number of events at a 1 kTon water Cerenkov detector are given in Appendix A. The effects of cuts on the minimum energy of detection (of the recoil electron) are shown in Table 1 in the Appendix.

2.2 Neutrinos from Stellar Collapse

Typically in a type II supernova explosion, neutrinos and antineutrinos of all types are emitted. The electron type neutrinos are expected to have an average energy of about 12 MeV with a Fermi distribution. The electron antineutrinos have an average energy of 16 MeV, where as the other species have a higher average of about 25 MeV. The energy spectrum is approximately given by the Fermi distribution with highest energies in the range of about 80 to 100 MeV.

Typically in a water Cerenkov detector, the charged current excitation of the oxygen nucleus contributes only a small percentage of events if one assumes that the neutrino flux is unchanged at the detector as compared to the flux at source. This is primarily due to the high threshold of about 15 MeV in CC excitation in the oxygen nucleus. In the presence of mixing, after imposing the known constraints, the ν_e and $\nu_{\mu,\tau}$ spectra are interchanged. As a result, a part or whole of $\nu_{\mu,\tau}$ flux appears as the ν_e flux at the detector. Because the original $\nu_{\mu,\tau}$ spectrum is hotter, it leads to increased number of CC nuclear excitations. Using the spectral information from the supernova neutrino emission, the increase may even be as large as a factor of 20 in the ν_e CC sector. See Table 2 and Appendix B for details of events in all sectors. Here, the effects of cuts on the recoil electron energy are also shown. Interestingly enough the neutrino- (and antineutrino-) nucleus CC events are backward peaked with respect to the supernova direction unlike the neutrino (antineutrino) electron scattering events which show a marked preference to the forward direction. While mixing does not deplete the forward peaked events on electron targets (in fact it increases slightly because of the increase in average energy), it results in a remarkable enhancement of the backward peaked events. This signal is model independent since the isotropic events due to $\bar{\nu}_e p \rightarrow e^+ n$ events provide a large overall normalisation flux.

Given that the nearest galaxy Andromeda is about 700 Kpc away, any experiment which aims to detect neutrinos from a supernova event every few years should have a sensitivity to probe distances of the order of 2-3 Mpc assuming that a core collapse takes place in a typical galaxy once in fifty years. This immediately puts the active mass of the detector system in the megaton range given the small cross section of neutrinos of energies greater than 10 MeV. Since only one supernova, namely SN1987A has been detected through neutrinos, a data set of approximately one SN per year accumulated over several decades will be of enormous importance to stellar astrophysics.

2.3 Short and Long Baseline Experiments with Neutrino Factories

Muon storage rings are being seriously considered as a first step to a $\mu^+\mu^-$ collider. The neutrinos are emitted in pairs $\nu_\mu, \bar{\nu}_e$ or $\bar{\nu}_\mu, \nu_e$ from μ^- or μ^+ decays. Neutrino beams resulting from muon decay will have a precisely known flux, well defined energy spectrum, and unprecedented intensity. Very long baseline neutrino oscillation experiments become possible with such neutrino sources. Furthermore, they can test whether the dominant atmospheric neutrino oscillations are $\nu_\mu \to \nu_\tau$ and/or $\nu_\mu \to \nu_s$ (sterile), in addition to determining the $\nu_\mu \to \nu_e$ content of atmospheric neutrino oscillations, and measure the $\nu_e \to \nu_\tau$ appearance. Depending on the oscillation parameters, they may be able to detect earth matter and CP violation effects and to determine the ordering of some of the mass eigenstates. An important feature of a detector for this application is muon charge identification in the detector (if possible).

Several possibilities for the baseline experiments are already under consideration. Two of these possibilities are Fermilab to MINOS (soon to operate with a traditional neutrino source) and Fermilab to Gran Sasso which is under consideration for later application with a neutrino factory. In the first case the base-length will be 732 kms. The anticipated number of charged current events at this distance is nearly 20,000 per year with the neutrino factory. There are also proposals to have baseline experiments from CERN to Gran Sasso (OPERA and ICANOE).

To disentangle matter effects one needs data from two experiments with different base lengths. An INO will have a baseline of about 10,000 kms from FermiLab and the data from this experiment will be extremely useful in determining neutrino parameters. This is perhaps the longest base length one can envisage in addition to providing reasonably dense matter in-between, during the long passage through the earth. Such a set-up will have a geometry where the neutrinos barely graze the core; hence core-matter effects may not be large. The experiment from Fermilab to Gran Sasso misses the core entirely. The combination of different baselines to INO, for example from CERN and/or KEK in addition to Fermilab, will provide leverage for unentangling the oscillation solutions.

Another attractive feature of this proposal is that the storage rings will perhaps be built in about ten years time. This is also the approximate time needed to build a neutrino detector including planning, building, calibration, etc. Unlike other proposals, this will be a completely new, and front line experiment without the risk of being outdated even before a beginning is made. By necessity, this proposal must become a part of an international setup. as it involves availing the beam from a remote source,

2.4 Global radioactivity in the earth

The antineutrino $\bar{\nu}_e$ spectroscopy can be used to measure the separate global abundances of ^{238}U and ^{232}Th. The total internal heat in the earth is of the order of 40 Terra Watts (TW). Of this about 40 percent or 16 TW is supposed to be due to the radiogenic heat. Models of the earth disperse this heat equally between the core and the mantle. Within the mantle the heat is generated mainly in the continental crust and a much smaller amount in the oceanic crust. A practical way of studying this distribution is to detect antineutrinos through the reaction $\bar{\nu}_e p \to e^+ n$ since all the antineutrinos essentially reach the surface. The present

sub-MeV threshold neutrino detectors can effectively be used to detect the neutrinos. However, the complete mapping of the origin of radiogenic heat, hence the detailed structure of earth matter, depends on putting an array of such detectors at various locations with contrasting geological features. The conceptual foundations of the geophysical structure, dynamics and evolution of the earth depends on such detailed information.

2.5 Nucleon Decay

One of the most important quests in all of physics remains the search for nucleon decay. The observation (or lack thereof) provides tests of elementary particle structure at the unification scale, not accessible to accelerator experiments. The present best limits on the mode of $p \to e^+ \pi^o$ are at a lifetime of 3×10^{34} years (from SuperK). These may be pushed to 10^{35} years. Current predictions from theory range upwards by several orders of magnitude, but nucleon decay could well be found at less than 10^{35} years. Many SUSY models unfortunately favour nucleon decay modes with K's, which have atmospheric neutrino background, and for which SK will probably not do much better than 10^{34} years.

A megaton detector contains 6×10^{35} nucleons. Given such a detector and the forthcoming more precise determinations of atmospheric neutrino fluxes and cross sections, it should be possible to seriously confront models with such an instrument (we discuss one realization below).

2.6 Others

Most of the physics goals mentioned above need underground laboratories in order to reduce the background. No matter what the main physics goal is, it is always possible to incorporate changes/additions such that one can also look at outstanding problems. One such problem is that of neutrino-less double beta decay, which is important in its own right. There are also possibilities of doing geophysical and biological experiments under extreme conditions, such as provided by an under-ground laboratory.

3. Some Ideas about the Detectors

The following paragraphs summarise a few ideas on the concepts for a new detector guided by the physics discussions.

3.1 Mega Water Cerenkov Detector (MWCD)

One avenue for exploration we have discussed involves an extension of the approach already demonstrated by the IMB, Kamioka and SuperKamioka detectors, employing Cerenkov radiation from interactions or decays in enormous volumes of water viewed by a surrounding surface of photomultiplier tubes. The largest of these, SuperK, has now been in operation for 4 years, and is near saturation of its physics capabilities—typically, further accumulation of data is expected to only improve statistics of already-observed data. The

SuperK detector has approximately 10 thousand photomultipliers and a contained volume of 33 kilotons, and fiducial volume (2 m all around) of 22 kT. The threshold is several MeV. We can gain greatly by raising the threshold of a proposed detector to about 10 MeV, and reducing the percentage area coverage from 40% for SK, to 2%, similar to that employed in IMB. In fact the IMB detector had a threshold of approximately 10 MeV. This then leads to a gain of approximately a factor of 20 in the dominant cost of photomultipliers and electronics.

The second area for improvement we have considered is in terms of size. By making the linear dimensions larger by a factor of two from SuperK, we gain more than as the cube in fiducial volume: we would get a 220 kT volume for nucleon decay, and 270 kT for SN neutrino detection. Five of these units would then yield 1.1 MT for nucleon decay and 1.35 MT for SN.

This detector might be put in a long tunnel of about 80 m diameter and 400 m length. Orienting this array to point towards a neutrino factory might be beneficial as well (or towards a local possible source of neutrinos such as the galactic center). One detector might be constructed, with the others following in a few years. An existing railway tunnel might, for example, be used to provide initial access. We estimate that the cost of the optical detectors, electronics and infrastructure (water filtration) would be less than $10M per module. Excavation costs and those of tank (or cavity liner) and mechanical structure, remain to be studied, as these depend heavily upon location, type of rock and access.

This detector would answer every one of the high profile physics issues we have discussed—all of which require data from an instrument in the megaton class. This would, of course, not address the issue of solar neutrinos below 10 MeV, and terrestrial neutrino detection; however, we feel that that the solar neutrino area below 10 MeV will be well explored by the time this instrument would come into operation, at least ten years from now. This detector would be the world's best in nucleon decay, supernova neutrino detection, atmospheric neutrino measurement, long baseline neutrino factory detection of muon neutrinos, searches for point sources of neutrinos in the energy range below about 1 TeV, searches for neutrinos from GRBs, and measurements of the total neutrino flux from the sum of all supernovae throughout the universe. Note that a megaton instrument can easily detect the initial burst of neutrinos from the in-fall stage of stellar collapse, out through the whole galaxy.

The group also identified the following topics for further study with respect to the Mega Water Cerenkov Detector: (1) Search for suitable location in consultation with mining engineers. It could be an existing tunnel or a mine. The detector needs a cavern of approximate length 400 meters with a cross section of 30 meters across. (2) Study also the excavation and cavity lining techniques. (3) Look into stimulation of PMT manufacture in India with possible cooperation from international companies. Also seek alternatives to PMT's. (4) Look into water purification. (5) Set up software Monte Carlo and study the performanance. (6) Pursue studies of all physics goals with respect to the MWCD. (7) The need to send some physicists to work at other neutrino labs in order to gain experience. (8) Seek international cooperation and collaboration for the project with an Indian lead.

3.2 An Underground Neutron Detector for SN Neutrinos

A possible proposal that can be built with the available expertise, and also possibly available material, is a supernova detector. The detector is in this case an array of neutron counters, possibly spread over a large volume, by drilling holes in either a mountain base or a mine with sufficient shielding. This process employs an enormous amount of earth (megatons) as a neutron source. The neutrons are produced when neutrinos with energies above 20 MeV interact with the surrounding rock. Both supernova explosions (short pulse) and integrated neutrino events from a large number of supernovae may be tracked with such a detector.

For a supernova explosion, this may infact be a real time detector. With an appropriate design, such a detector can be combined to measure penetrating charged particle fluxes (e.g. through-going upward muons from astrophysical neutrinos) and for proton decay experiments (Kaon decay mode which is complementary to that measured in water Cerenkov detectors) with a denser array of the detector in part of the experiment. Most worrisome for this experiment are the natural neutron fluxes in the earth due to radioactive decays. The limiting sensitivity of such an experiment depends upon locating very low radioactivity rock in a sufficiently deep location. This requires further investigation in India, and costs need study but may be substantially less than a Cerenkov detector.

3.3 DAEDULUS: Space Based Neutrino Detector

This project is somewhat far into the future since it would require an active space program if it is to be adopted for INO, but it is very interesting. Basically it is an idea for a neutrino detector in space. Consider placing a neutrino detector with enough shielding (from heat, background, etc) in a highly elliptic orbit around the Sun. One could then measure the neutrino flux as a function of the distance from Sun. Decent statistics would require the space based neutrino detector to be in orbit for a sufficient amount of time. It provides a unique method to understand neutrino oscillations, which may be crucial in the instance of several scenarios of oscillations not now resolved.

One can also watch for supernovae neutrinos and gamma-ray bursts, getting accurate location by timing relative to terrestrial detectors (as is now done for gamma ray detectors). Further potential applications include measurement of the ratio of pp to pep neutrino fluxes from the Sun, study of cosmic ray isotropy and spectrum over one AU, and the study of possible g-mode effects in cosmic rays.

Background neutrino effects are taken care of since there is no background from terrestrial radioactivity, no reactors in the vicinity, and no atmospheric cosmic ray muons and neutrinos. However charged and neutral cosmic rays form a real background.

The techniques involved are similar to the LENS proposal. The difference is that here it is proposed to isolate pure ^{176}Yt (about two tons of this gives the same sensitivity as LENS with 200 tons)). Such a compact detector can be flown in some thing like a shuttle. Scaling rates up from the present estimates for LENS there will be about, $g \times 300$ (pp events), $g \times 160$ (Be events), $g \times 15$ (pep events) per year. Here g is the gain from the distance factor depending on how close the detector can get to the Sun. We aim for a g-factor of 100, but even if $g \sim$ five to ten, detecting pep neutrinos becomes a real and exciting possibility.

4. Manpower requirements

- A chief problem area is the availability of a sufficient number of trained physics personnel in India. With declining number of students getting into the science stream, and with the numbers going down in the intake of Ph.D's in various institutes and universities, a large experimental facility is bound to have manpower problems. The initiative must have enough breadth to be able to produce sufficient number of Ph.D's, even though this is not a guarantee that students will actually join such a project. The very presence of such a world class project would surely attract many talented young people.

- An effort like INO would require large numbers of people involving both research Institutes and Universities and probably funded by many funding agencies.

- Furthermore, the very nature and magnitude of the proposal also demands international collaboration in order to be fully successful.

4.1 Summary

We have listed various points that were raised during four sittings and many less formal discussions. While difficulties are many, there are also attractive physics possibilities. A few stand out:

1. Initiation of studies and design, and ultimately construction of a large new neutrino facility starting now blends well in time with the exploitation of present instruments and is in synchrony with the construction of a possible (probable, according to many) neutrino factory.

2. A strong motivation for locating a detector in India is the near equatorial location, permitting observation of neutrinos passing through the earth's core. The detector may be useful for precision studies like fixing the full MNS matrix (the equivalent of the CKM matrix for neutrinos), etc. In any case the location of a detector near the equator provides a view that sweeps the entire celestial sphere once per day for upcoming neutrinos.

3. The giant water Cerenkov detector goes a long way in addressing many of the physics goals mentioned above. At the megaton scale such an unprecedentedly sensitive instrument will yield good statistics at reasonable cost while only trading off low threshold solar neutrino physics (probably well studied by the time this experiment operates anyway). The greatest advantages are, (1) that it will give a good understanding of the higher end of the solar neutrino spectrum, (2) it can survey supernova neutrinos at megaparsec scale as well as measure SN events inside our galaxy with great precision, (3) it will serve as an excellent proton detector, and (4) it can also be used in a long base line experiment. In summary it may address all the physics issues outlined here and probably many more.

In short, we have identified some important and worthwhile physics opportunities. Each of these needs to be examined more carefully with the INO in view. While it's premature

to expect that any funding proposal could come out from the short time-duration of the WHEPP-6 meeting, it is hoped that the group has identified viable concepts for further investigation over the next few months. At that stage, it may be pertinent to undertake a more detailed feasibility study for such a detector.

Appendix A: Solar neutrino event rates

The solar neutrino rates for a 1 kTon water-Cerenkov detector are shown in Table 1. It is seen that the event rate falls sharply with increasing threshold.

E_{min} (MeV)	Event rate
8.0	.90
10.0	.25
12.0	.03

Table 1. Event rates per day at a 1 kTon water Cerenkov detector from solar neutrinos.

Appendix B: Supernova events

The number of supernova events during stellar collapse are determined by the interaction of all flavours (and antiflavours) with the material of the detector. For a water-Cerenkov detector, this includes scattering off electrons, protons and oxygen in the water. These give events that are forward-peaked, isotropic and backward peaked respectively. Table 2 shows the events accumulated by a kiloton detector from events from a supernova 10 KPc away. There are few oxygen events without neutrino oscillations. However, assuming a 3-flavour oscillation scenario consistent with solar and atmospheric neutrino data, we see a significant enhancement (by a factor of 6) of the oxygen events. This is because these events are enhanced by mixing of the heavier flavours into the electron neutrino spectrum. The hotter spectrum then gives a large event rate which is strongly backward peaked. Increasing the threshold of the detector from 8 to 12 MeV severely decreases the forward rate (by 30 and 45% with and without oscillations, while there is only a marginal decrease in the isotropic rates (10%) or the backward rates (few %) in the presence of oscillations.

E_{min} (MeV)	Events per kTon						Ratio, $R = N/N_0$		
	N_0^F	N_0^I	N_0^B	N^F	N^I	N^B	R_F	R_I	R_B
8.0	4.5	281.2	5.0	8.0	329.1	32.7	1.8	1.2	6.5
10.0	3.3	270.1	4.9	6.7	320.8	32.5	2.0	1.2	6.7
12.0	2.4	254.8	4.7	5.6	308.9	32.2	2.3	1.2	6.9

Table 2. Number of forward, backward and isotropic ($i = F, B, I$) events with (N^i) and without (N_0^i) oscillations for a supernova explosion at a distance of 10 KPc, for a 1 kTon detector. The oscillation is assumed to be maximal.