The India-Based Neutrino Observatory

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ABSTRACT

The Indian effort to build an underground laboratory for rare processes is outlined. The flagship experiment to measure atmospheric muon neutrinos and antineutrinos, separately, will target the open problem of ordering of the three tiny neutrino masses. This, together with other experiments being conducted throughout the world, will help address CP violation in the neutrino sector, which could further our understanding of why there is a preponderance of matter over anti-matter in the universe. Efforts are also underway to set up cryogenic detectors for neutrinoless double beta decay in ^{124}Sn and for dark matter using silicon, respectively.

INTRODUCTION

The neutrino is one of the most enigmatic, and perhaps the least understood, of the fundamental particles that we know. In the Standard Model (SM) of particle physics, whose predictions have been extensively verified, the three kinds of neutrinos belonging to the electron, muon and tau lepton families have zero masses. The phenomenon of transformation of neutrinos from one type to another, called neutrino oscillation, was discovered by the Super-Kamiokande collaboration in 1998 [1] and subsequently by the Sudbury Neutrino Observatory in 2002 [2]. Neutrino oscillations require neutrinos to possess a non-zero mass. While the last and key ingredient of the SM, viz. the Higgs boson, has been discovered recently [3], neutrino oscillations strongly suggest physics beyond the SM.

Neutrinos can be described in terms of their three flavor or mass eigen-states, the two descriptions connected by a 3 3 complex matrix. If we discover one or more species of sterile neutrinos this matrix would have to be suitably expanded. Presently, efforts are being made throughout the world in order to pin down the parameters constituting the matrix, which are the three mixing angles (θ_{12}, θ_{13}, θ_{23}), three masses (m_1, m_2, m_3) and a CP phase angle (which increases to three if the neutrino is its own antiparticle). Experiments addressing neutrino oscillations measure the differences in the squared masses. The results of solar neutrino experiments can be understood when matter effects on the electron neutrinos, propagating outward from the core of the sun, are taken into account. This fixes the ordering of the masses of the m_1 and m_2 mass eigenstates, namely, $m_2 > m_1$. Data from accelerator based experiments result in a value for $|m_3^2 - m_2^2|$. Since this is about 30 times larger than the corresponding difference for m_1 and m_2, m_3 could be larger or smaller than m_1 and m_2. These situations correspond to the normal and inverted mass hierarchies. Why is it important to know which of these hierarchies is followed in nature? Accelerator based experiments measuring neutrinos at long baselines usually have a hierarchy-CP phase ambiguity. A clear answer on the mass hierarchy could help measure unambiguously a possible CP violation in the neutrino sector. If it turns out to be sufficiently large it could help solve the matter-antimatter asymmetry in the universe.

THE INDIA-BASED NEUTRINO OBSERVATORY (INO)

Experimental evidence for atmospheric neutrinos was found in a deep mine at Kolar Gold Fields (KGF) by the TIFR-Osaka-Durham collaboration [4] and almost simultaneously by a team led by Reines working at a gold mine in South Africa [5]. However, building larger detectors in the mine, especially at the deepest level, which

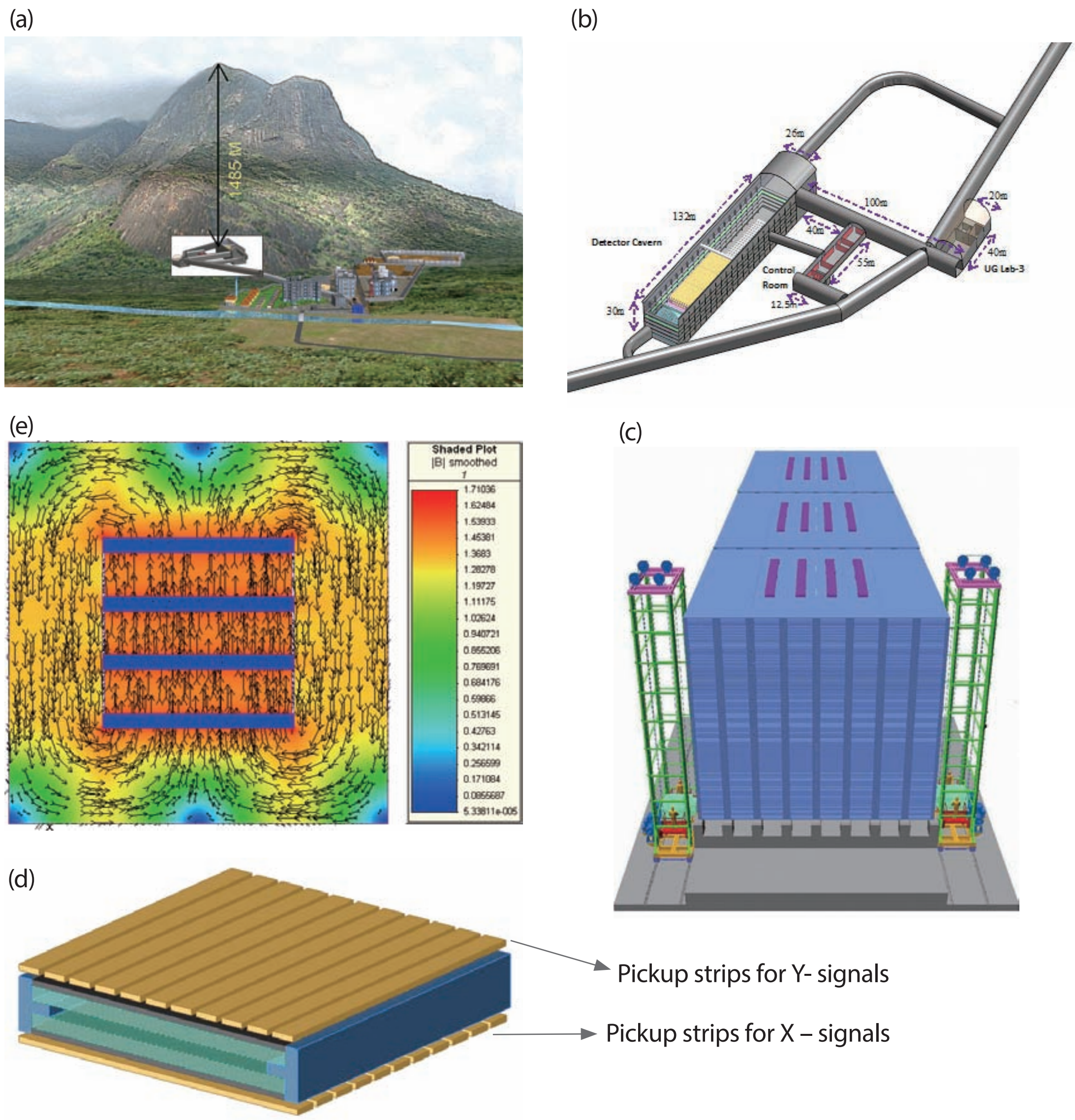

Fig. 1: From top left clockwise: (a) view of the mountain inside which the INO caverns will be located; (b) cavern complex; (c) schematic of ICAL magnet with RPC handling trolleys; (d) schematic of glass RPC with glass gap, graphite coating for application of high voltage and pickup strips on either side of gap in X- and Y-directions; (e) simulated magnetic field across 16m 16m area. The color code indicates the B-field strength in Tesla.

is the ideal location, was not possible. Also the KGF became economically less competitive compared to other gold mines and were eventually closed down. Meanwhile, in the late 90's an effort began to revive the culture of underground experiments in India, focusing on neutrino experiments. Building such a lab at the end of a tunnel, such as at Kamioka in Japan and Gran Sasso in Italy, was a better option for housing large detectors. At around this time the field of neutrino physics was becoming very interesting in view of results from the Kamiokande-I, Irvine-Michigan-Brookhaven and later Super-Kamiokande experiments, which turned the background for proton decay (for whose lifetime only upper bounds could be placed) measurements into a signal for atmospheric neutrino oscillations!

The idea of building an underground laboratory in India began with the signing of a MoU by the directors of six institutes of the Department of Atomic Energy in 2002. Early on it was decided that we would build a 50-100 kton magnetized iron calorimeter (ICAL) to study atmospheric muon neutrinos. This would be unique in that

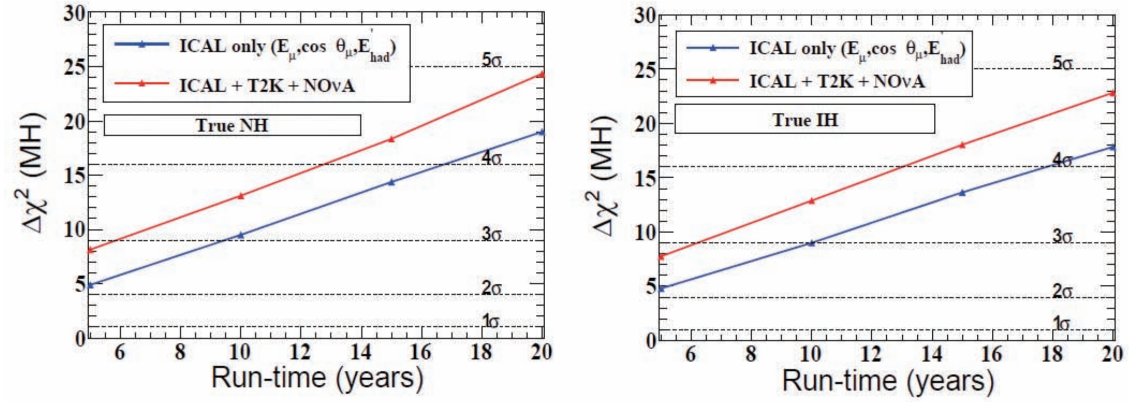

Fig. 2: Plots showing the hierarchy sensitivity of ICAL alone and when combined with anticipated data from T2K (integrated flux of 8 10^{21} protons on target) and NovA (3 years runs each in neutrino and anti-neutrino mode).

it would have the capability of distinguishing between neutrino and anti-neutrino induced events using the so-called charged current interactions which produce muons of opposite charge, respectively. A similar proposal, MONOLITH, had been considered by an Italian group with a somewhat smaller, 32 kton detector. Simultaneously, R&D was started on simulations (both for neutrino detection and the magnet) and the active detector element. The choice for the latter fell on the resistive plate chamber (RPC) which is a position sensitive, fast gas detector. The first document was prepared in May 2006 [6] and the latest one is the white paper on the physics capability of ICAL at INO [7]. There are about 25 national labs and universities collaborating in the INO project. The funding for the project, of about 1500 crore rupees (approx. 200 M$), was approved by the central government in December 2014.

INO will be an underground laboratory located in the southern Indian state of Tamil Nadu at Pottipuram. The experimental halls will be constructed at the end of a two km long tunnel with about one km rock cover all round. This will reduce the cosmic ray background by about a factor of a million, enabling low background experiments to be carried out. While the ICAL detector for measuring atmospheric muon neutrinos will be the largest in the underground laboratory, there are at least two other experiments which make use of the low cosmic background to search for neutrinoless double beta decay in ^{124}Sn and a silicon detector for directly detecting dark matter particles.

The main scientific goals of the ICAL experiment are (i) the determination of the ordering of neutrino masses, known as the mass hierarchy problem viz. whether $m_3 > m_2 > m_1$ (normal hierarchy) or $m_2 > m_1 > m_3$ (inverted hierarchy); (ii) a more precise measurement of the mixing parameters θ_{23} and Δm_{23}^2; (iii) confirm or rule out the anomalous Kolar events, and (iv) together with long baseline accelerator experiments, address the very fundamental problem of the predominance of matter over antimatter in the universe [8]. The ICAL detector is best suited for making measurements of muons (distinguishing μ^+ and μ^-), and hence, of primarily muon neutrinos and anti-neutrinos separately.

The hierarchy sensitivity of the ICAL detector has its origin in the “matter effect” where the effective neutrino mass and mixing angles change when neutrinos propagate through any material such as the earth. The change is different for neutrinos and antineutrinos, something which can be used in measurements which can discriminate between the two such as those with the magnetic calorimeter ICAL. The large range of energies (1-10 GeV) and propagation distances (1-13000 km) of atmospheric neutrinos and the ability of ICAL to separately measure neutrinos and anti-neutrinos enables a very important problem of mass ordering, known as the mass hierarchy problem, of neutrinos to be addressed. The result of a sensitivity study, both from ICAL alone and together with data from accelerator experiments, is shown in Fig. 2 [9].

The precision measurement of Δm_{32}^2 and $\sin^2 2\theta_{23}$ is another goal of ICAL [10]. Similarly a handful of events, the so called Kolar events, have been observed in the KGF experiments (~1965–1990) at depths of about 2.3 km. At these depths, cosmic ray muons constitute a negligible background. These anomalous events were then ascribed to a new particle produced in neutrino-rock interactions which emerges from the rock to decay in the air volume. This should then have been seen in accelerator, which turned up negative. A possible recent explanation [11] could be examined at INO [12]. Another study relates to the sensitivity of ICAL to primordial magnetic monopoles [13].

There are also other experiments for which R&D or feasibility studies are ongoing. The first aims to measure neutrinoless double beta decay in ^{124}Sn using a tin bolometer cooled to a temperature of $\sim$10 milli-Kelvin. The first thermal signals from a small sample of natural tin have been observed [14]. Another group is aiming to build a cryogenic silicon bolometer to study dark matter [15]. Finally, there is interest from university groups to set up a facility to measure cross sections of interest to nuclear astrophysics [16].

The present status is that the financial sanction for the INO project has been received. The engineering prototype ICAL detector, which will have a size of 8m 8m 2m, will be built at IICHEP, Madurai, which will also oversee the activities at the underground laboratory. Procurement and development for this project has already begun and is expected to be completed in the next 2 years. Simultaneously a consultancy contract for the design of the underground tunnel and cavern will be awarded shortly. However, some important approvals from the state government authorities for construction at the IICHEP and INO sites are still awaited.

In summary, the India-Based Neutrino Laboratory is poised for building an underground laboratory in Pottipuram, Tamil Nadu in the southern part of India. The flagship experiment aims to address the neutrino hierarchy problem using a 50 kiloton iron calorimetric detector. The underground lab will also house other experiments that benefit from the low cosmic ray background.

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Dr. Vivek Datar is a senior professor at the Tata Institute of Fundamental Research (TIFR), Mumbai since May 2015. He obtained his PhD from the University of Mumbai in 1983 and did post-doctoral work at IPN, Orsay, France and SUNY (Stony Brook), USA. Before moving to TIFR he was at the Nuclear Physics Division (NPD), Bhabha Atomic Research Centre (BARC) [1975-2015]. He was a senior professor of the Homi Bhabha National Institute (HBNI) and dean-academic for Physical and Mathematical Sciences, BARC. He was also the head of NPD at BARC, Mumbai, and an adjunct professor at the School of Natural Sciences, TIFR. His areas of interest include low energy nuclear physics, tests of conservation laws and symmetries and neutrino physics. Presently he is part of a national effort, the India-Based Neutrino Observatory Project, which aims to build a large underground laboratory at Pottipuram, Tamil Nadu.

Prof. Naba K. Mondal is the project director of India-Based Neutrino Observatory and a senior professor at the Tata Institute of Fundamental Research (TIFR), Mumbai. He was involved in several important particle physics experiments and played a key role in the Kolar Gold Field (KGF) necleon decay experiment. He was involved in the DZERO experiment at Fermilab which discovered the top quark in 1995. He was the leader of the Indian group for designing and building the Outer Hadron Calorimeter for the CMS experiment at CERN, which discovered the Higgs boson in 2012. He is now involved in the development of an underground laboratory in India for carrying out research in the field of neutrino physics. He is a fellow of the Indian National Science Academy (INSA), the Indian Academy of Sciences (IAS), the National Academy of Sciences in India (NASI) and the World Academy of Sciences for the advancement of science in developing countries (TWAS). He is also a J. C. Bose National Fellow.