Discussion meeting on an Underground facility in India

An in-person meeting was held at TIFR Mumbai on August 6 and 7, 2022 to gauge the interest of the Indian scientific community in performing experiments at a possible underground facility with a rock overburden of 1.5 – 2 km. The meeting was attended by about 80 participants, out of which about 25 were from TIFR, while 55 were from other institutes and universities in the country. Proposals regarding scientific activities that will become possible with the availability of such a facility were invited through an email announcement circulated widely among the scientific community in the country in the areas of nuclear physics, high energy physics, astroparticle physics, biology, geology, etc. The proposals were presented and deliberated on during the meeting.

The project proposals can be broadly categorized into three types:

- Experiments where we clearly have an advantage over the rest of the world, from the point of view of existing expertise in technology and human resource, availability of material, geography or topology, or new niche ideas that have not been tried out yet elsewhere. In such projects, we can be extremely competitive with the rest of the world and may even be the first ones to discover new phenomena or resolve long-standing scientific puzzles.
- Projects where Indian scientists are a part of international collaborations based elsewhere and would like to perform R&D / prototype testing in the country. This would enable the Indian scientists to play significant roles in the international projects at the forefront of knowledge and fulfil the in-kind commitments of the country in these projects. Over the long run, this would lead to technology-building, and prepare the foundation for the future generations of Indian scientists to lead major projects in these areas.
- New ambitious and challenging ideas, some of which are still in the inception phase that need a clean environment, free of cosmic-ray background. Although one may not think of building an underground facility just for these, the mere availability of an underground facility would allow the Indian scientific community to conceive and implement such projects. Once the infrastructure of an underground facility is available, the marginal investment needed for implementing these projects would be much smaller and performing these niche experiments in a timely fashion will be feasible.

The overall vision of the community that emerged from the in-depth discussions at the meeting is summarized in the Table on the next page.

The meeting highlighted the need for a multi-cavern underground laboratory with a minimum of 1.5 km rock overburden to enable the Indian scientific community to pursue a variety of challenging science problems, which cannot be explored otherwise. Such a facility will not only boost the national scientific programme but will also stimulate the advanced detector and associated technology development in the country and provide an ideal training ground for ambitious young scientists and engineers.

Science program/area	Academic bodies involved/interested in the program
Atmospheric neutrinos	*ICAL collbaration* - Aligarh Muslim University, The American College Madurai, Banaras Hindu University (BHU), BARC, HRI, IIT Bombay, IIT Madras, IMSc, IOP, JNU, Panjab Agricultural U, Panjab U., PRL Ahmedabad, SINP, TIFR, U. of Calicut, U. of Calcutta, U. of Delhi, U. Kashmir, U. Lucknow, U. Mysore, UPES- Dehradun, Utkal U., VECC, UPES-Dehradun.
Solar Neutrinos	BARC, Central University of Karnataka, Heavy Water Board (DAE), IMSc, TIFR Collaboration with Brookhaven National Laboratory (USA).
Neutrinoless Double Beta Decay	BARC, Central U. of South Bihar, IIT Ropar, IMSc, Panchanan Barma University, Coochbehar, TIFR, U. Lucknow, VECC.
Dark matter search	BARC, NISER, SINP, Univ. of Hyderabad, VECC, Collaboration with Texas A&M University (USA).
Low-energy underground accelerator for nuclear astrophysics	Aligarh Muslim University, Banaras Hindu University, BARC, Calicut U., Central University of Haryana, Central University of Kerala, Cotton U., IIT (ISM) Dhanbad, IIT Ropar, IIT Roorkee, Mangalore U., Panjab U., TIFR, VECC, UGC-DAE CSR, U. Calcutta, U. Delhi, Visva Bharati U.
Rare nuclear decays with novel detectors	BARC, IIT BHU, IIT Dhanbad, IIT Ropar, North Bengal University, NPL, SINP, TIFR, U. of Delhi, U. Lucknow, VECC, VIT.
Other areas : Geophysics, Biology ….	Indian Institute of Geomagnetism, …..

1. Neutrino oscillation physics

1.1 Iron Calorimeter (ICAL) for atmospheric neutrinos

The Iron Calorimeter (ICAL) experiment has been approved by the Govt. of India in 2015. The ICAL detector will be a 50 kiloton electromagnet made of alternating layers of iron plates as the neutrino target and resistive plate chambers (RPCs) as active elements. The unique capabilities of the detector are (i) accurate reconstruction of the energies and directions of muons produced from the interactions of atmospheric neutrinos inside the detector, (ii) identification of the charge of these muons, thus distinguishing between the originally interacting neutrinos and antineutrinos, and (iii) detection of hadrons arising from the neutrino measurements and measuring their energies.

ICAL would be sensitive to the neutrino energy range of 1–25 GeV, which is complementary to the energies covered by other atmospheric neutrino detectors like SuperKamiokande / Hyper-Kamiokande (0.2–5 GeV), Deep Core, ICECUBE (5–100 GeV), and ORCA, KM3NET (3 – 30 GeV). These capabilities allow ICAL to probe neutrino properties within and beyond the Standard Model of particle physics, as well as to address physics issues even beyond neutrinos. For example, it can (i) identify the neutrino mass ordering by observing atmospheric neutrinos, (ii) observe Earth matter effects on neutrinos, and the MSW / parametric resonances of neutrinos travelling through the Earth, (iii) observe the oscillation dip and valley pattern in muons, (iv) identify interactions of neutrinos beyond the Standard Model of particle physics -- non-standard neutrino interactions (NSI), violation of fundamental symmetries like Lorentz invariance or CPT invariance, flavor-dependent long-range interactions, neutrino decay, decoherence (v) look for possible new particles like sterile neutrinos, magnetic monopoles, dark matter, and (vi) obtain information on the internal structure of the Earth (the so-called Earth tomography) using weak interactions. It can also play an important role in multi-messenger astronomy.

Extensive R&D has been performed for the ICAL detector over two decades. This includes the development of the Resistive Plate Chambers (RPCs) that are the active elements of the detector, the electromagnet itself, the electronics and related instrumentation, as well as physics potential studies of the detector through simulations. A small prototype, mini-ICAL, has been in operation in Madurai since 2018, and is taking data for cosmic-ray muons.

The details of the ICAL experiment and the science it can address is already available in *Pramana 88 (2017) 5, 79*, e-Print:1505.07380 [physics.ins-det]. The ICAL collaboration consists of scientists and engineers from Aligarh Muslim University, The American College Madurai, Banaras Hindu University, BARC, HRI, IIT Bombay, IIT Madras, IMSc, IOP, JNU, Panjab U., PRL Ahmedabad, SINP, TIFR, U. of Calicut, U. of Calcutta, U. of Delhi, U. Kashmir, U. Lucknow, U. Mysore, Utkal U., VECC, etc.

1.2 Deuterated Liquid Scintillator for solar and supernova neutrinos

The Deuterated Liquid Scintillator (DLS) project proposes a 1 kt-class detector with either a hydrocarbon-based liquid scintillator with the hydrogen replaced by deuterium, or water-based liquid scintillator dissolved in heavy water ($D_2 0$), instrumented with ~2500 PMTs. This allows

- neutrino and antineutrino detection, with sensitivity to all flavors
- low energy, high resolution measurements using the scintillator light along with Cherenkov, to reduce threshold and increase light yield.

A key target of the DLS project would be to measure solar neutrinos in the 2-5 MeV energy, providing the first stringent test of the theory of solar neutrino flavor mixing, that is the so-called large-angle MSW theory. The ability to detect low-energy electron neutrinos provides a unique opportunity to do this. Such experiments, if located close to the equator, would also be sensitive to the matter effects through the core of the Earth, which give rise to the so-called "day-night effects" which have not been conclusively established so far. This could be an opportunity for India to make a major contribution to the understanding of solar neutrinos, and the feasibility of specialized detectors for this purpose should be explored. An all-flavor detection of supernova neutrinos, possible at this detector, can also play a crucial role in extracting the first observational signature of collective neutrino oscillations.

Preliminary works being carried out include synthesis and testing of ordinary scintillator, interfacing with detectors, studies of DLAB, DBenzene, DXylene synthesis, low-background set-up + U/Th testing of D2O, rocks etc., closed-loop purification setup with Water-based liquid scintillator and PMTs, detector simulation in the GEANT framework, and some physics studies. Participation of the larger community is anticipated and welcome. For example, collaborations with national and international colleagues with experience in ultra-radio-purification, deuterium chemistry, PMT handling, etc. would bring greater value to the proposal.

Indian scientists actively pursuing the above include those from BARC, Central University of Karnataka, Heavy Water Board (DAE), IMSc, TIFR along with BNL, USA.

1.3 Indium-based detector for solar neutrinos

Neutrino observations focusing on specific aspects of solar neutrino would enrich our knowledge of the interior of the Sun. For example, the standard solar model predicts a line spectrum of Be-7 electron capture neutrinos. Such a line spectrum cannot be observed at any of the current neutrino detectors like Borexino or JUNO, since they are based on Compton scattering where the electron carries only an unknown fraction of the neutrino energy in each interaction. An Indium-based low energy electron neutrino detector could measure, in real time, solar neutrinos using the charged current interaction with a "peak" response to Be-7 neutrinos. Apart from an accurate measurement of the solar neutrino spectrum at low energies, it could be the first one to directly measure the temperature at the core of the Sun, by determining the width of the Be-7 spectral line. In addition, a more robust measurement of the neutrinos emerging from the CNO cycle is possible at such a detector.

Such a detector was envisaged in the US in 1976, and significant R&D has been carried out under the aegis of the LENS (Low Energy Neutrinos from the Sun) programme. The main challenge is the reduction of background from the -radioactivity occurring in Indium-115 itself. A small prototype had been successfully built in the shallow Kimbleton mine in the US. The Indium detector could be based on an In-doped liquid scintillator (LS) or a cryogenic In-bolometer. It could be built at a depth of 500-1000m. Expertise exists at Virginia Tech and BNL (USA) on metal-doped LS including water soluble LS, and collaboration to help develop this technology in Indian industry is possible. Development of a very different approach using quasiparticles in a superconductor of Indium is also possible at a detector development centre in the country. The technologies of liquid scintillator, metal loaded liquid scintillators, cryogenic detectors and LAPSD will find wide application in many other areas such as security, low noise electronics, and photon counting, respectively.

This idea is still in its inception phase in India and needs to be taken up by interested experts in neutrino physics and nuclear physics. This is an unexplored opportunity.

2. Neutrinoless Double Beta Decay

The mass and nature of neutrinos play an important role in theories beyond the Standard Model of particle physics. Whether neutrino is its own antiparticle, as proposed by Majorana, is still an open question. At present, neutrinoless double beta decay ($0\nu\beta\beta$/NDBD) is perhaps the only experiment that can reveal the true nature of the neutrino and provide information on the absolute effective neutrino mass. Given its significance, there is a widespread interest in the quest for $0\nu\beta\beta$ employing different techniques.

In India, a feasibility study to search for $0\nu\beta\beta$ in ^{124} Sn (the TIN.TIN experiment) has been initiated, led by the group from TIFR. The ^{124}Sn has moderate isotopic abundance ~5.8% and a reasonably high Q value of 2.28 MeV. Since the constancy of sum energy of two electrons defines the NDBD event, good energy resolution is of paramount importance. Cryogenic bolometers with excellent energy resolution and high sensitivity, are well suited for search of $0\nu\beta\beta$. Tin becomes superconducting below 3.7 K, and its specific heat has only lattice contributions for $T < 100$ mK. It can therefore be made into a high energy-resolution bolometric detector. The TIN.TIN proposal envisages a large size detector with enriched ^{124}Sn (50-90%), to be developed in 3 stages: 100 Kg, 500 Kg, and 1000 Kg. The time scale will be dependent on the availability of enriched tin.

A custom-built cryogen-free dilution refrigerator with a high cooling power of 1.4 mW at 120 mK, has been installed at TIFR for R&D related to prototype development. For mK thermometry, neutron transmutation-doped (NTD) Ge sensors have been developed indigenously. The TIFR Low Background Experimental Setup (TiLES) with a special low-background HPGe has been set up. TiLES has been extensively used for selection of detector materials and for understanding the neutron- and muon-induced backgrounds. Further, indigenously developed CsI and Ge crystals at BARC (for use in the Dark Matter experiment), rock samples from possible tunnel sites, etc. are also studied in TiLES. Muon Induced Neutron detector setup at TIFR (MINT) has been made and used to investigate neutron background issues. The best limits on the lifetime of the ^{94}Zr $\rightarrow$ ^{94}Mo double beta decay process have been reported from this setup.

A large-size detector for neutrinoless double beta decay, employing superconducting bolometers, will be a unique facility worldwide. The effort has already initiated the cryogenic bolometer detector and mK thermometry R&D in the country, which can also be implemented for other rare decay studies like dark matter searches. Germanium has been recognized worldwide as one of the most suitable materials for detecting neutrinoless double beta decay, and some of the Indian groups are participating in international collaborations like LEGEND. The availability of an underground facility will enable these scientists to set up R&D facilities for Ge detectors, which may be upscaled in a phased manner. This would ensure significant participation of Indian scientists

Indian scientists actively pursuing or planning for the above include those from BARC, Central University of South Bihar, IIT Ropar, IMSc, TIFR, U. Lucknow, VECC. There is a possibility of collaboration with international groups in such projects.

3. Dark matter search

Dark matter (DM) is the dominant component of mass in the Universe. The fundamental scientific question remains unanswered: the nature and type of particles DM is made of. A direct detection experiment involves the interaction of DM particles with detector material. They must be located in deep underground laboratories to avoid the effects of cosmic ray interactions that produce energetic neutrons that could mimic DM particles. Such an experiment can also look for additional exciting physics topics like fractionally charged particles. A clear observation of fractional charge would be very important since depending on the type of particle observed, it might mean that confinement breaks down under some circumstances or that entirely new classes of particles exist.

Indian groups, several of them already participating in international projects like SuperCDMS, PICO and Texono, are interested in (a) setting up DM search experiments in UGF India and (b) using the facility to carry out detector R&D in the area. This R&D would focus on the development of technology to enable the improvements in backgrounds and detector performance required to achieve these ever-growing compelling science goals.

The cross-section versus mass phase space for DM search shows unexplored areas in the low, intermediate and high mass regions. Three proposals were presented in this regard.

a) Cryogenic detector-based dark matter search involves a semiconductor (Si, Ge) or sapphire (Al_2O_3) based detector using photon and phonon-based detection techniques.

b) Scintillator-based cryogenic dark matter search will use detectors based on indigenously developed scintillator (CsI, tungstates, sapphire, GGAG) material.

c) Superheated liquid detector (SLD) based low mass DM search using $C_2H_2F_4$-like material is based on an acoustic signal detection technique.

It may be noted that the above techniques are sensitive to different masses of the dark matter particles. Small-scale prototypes of some of these detectors are already being developed and tested. Indigenous development of scintillator crystals has been initiated and a large size (~ 3 kg) CsI detector prototype has been successfully demonstrated. Prototype tests for scintillator and SLD detectors at the Jaduguda Underground Science Laboratory (JUSL, ~ 500 m depth) are underway.

The institutions involved in the above R&D are BARC, NISER, SINP, VECC. There is also foreign collaboration from Texas A&M University. The groups indicated the possibility of close collaboration with several international groups in such projects.

4. Nuclear physics and nuclear astrophysics

4.1 Low-energy underground accelerator for nuclear astrophysics

An underground laboratory can also offer the possibility of installing a MV-scale accelerator, which can enable the exploration of many reactions of interest to nuclear astrophysics. For example, some of the reactions relevant to He and C burning, BBN reactions, capture reactions with p-nuclei, etc. have very low cross sections and can only be studied with the help of accelerators that are located deep underground. Such a facility will also enable measurements of fission gamma rays relevant to fundamental nuclear physics.

An accelerator facility, with 400 kV (phase-I) and 5 MV single ended (phase-II), will be able to cover the energy range of interest including inverse kinematics. The accelerators will be based on electron-cyclotron-resonance (ECR) ion sources. It is envisaged that the phase-I may be built over 10 years, and the phase-II over the subsequent 5 years. Such a facility, coupled with a recoil mass separator (RMS) and windowless gas target will be a unique facility in the world.

The institutions interested in constructing and running such an underground accelerator are Aligarh Muslim University, Banaras Hindu University, BARC, Calicut U., Central University of Haryana, Central University of Kerala, Cotton U., IIT Ropar, IIT Roorkee, Mangalore U., Panjab U., TIFR, VECC, UGC-DAE CSR, U. Calcutta, U. Delhi, Visva Bharati U.

4.2 Rare nuclear decays with novel detectors

Gamma decay studies in an underground laboratory will provide new opportunities for studying rare decay processes in atomic nuclei. For example, one can

- Test the exponential decay law of radioactivity to extremely short time intervals as compared to the lifetime.
- Study rare beta decays of ground and isomer states in nuclei, like, ^{48}Ca, ^{96}Zr and ^{180m}Ta
- Search for new, previously undiscovered, alpha decays
- Study two-photon decay in atomic nuclei and its connection to nuclear polarizability, EOS and $0\nu\beta\beta$ decay.
- Perform direct measurements of neutrino mass from Electron Capture (EC) decay studies.
- Explore the applications of ultra-low gamma spectroscopy for material selection and testing (for micro-electronic components or in astroparticle physics experiments), environmental research (oceanography, climate science, atmosphere), and other possible industrial applications.

It is envisaged that one may set up an array of low background HPGe detectors based on the new generation of point-contact technology with electrical cooling. In addition, for higher multiplicity rare events, novel detectors are required with high efficiency, large granularity, good energy and time resolution along with imaging capability. One of the challenges for this project is to develop SiPM based readout technology with minimum dead-layer in the scintillator.

The institutions interested in this project are BARC, IIT BHU, IIT Dhanbad, IIT Ropar, NPL, SINP, TIFR, U. of Delhi, U. Lucknow, VECC, VIT.

5. Other areas

While the participants in the meeting were mainly from the nuclear physics, high energy physics, and astroparticle physics communities, it was recognized that underground laboratories worldwide are also hosts to scientists from other areas like geophysics and biology. Some representatives from the geophysics community participated in the meeting and presented their view.

5.1 Geophysics

An underground facility, combined with some surface infrastructure, is an opportunity for the quantification of noise while performing seismological measurements, by simultaneous measurements at the surface and underground. An underground location, if it provides a mechanically and electromagnetically shielded space, can also be used for the monitoring of seismic and magnetic signals as well as telluric currents. However, these are just preliminary thoughts, and more discussion among the Indian geophysicists is needed to figure out a concrete way of exploiting the availability of such a facility. It may be mentioned that the efforts to initiate such geophysics activities at JUSL are underway.

5.2 Biology

Understanding the effect of natural background radiation on living cells and their metabolism remains a topic of interest in biology. The underground laboratory opens a new research window for radiobiology to extend the study of living organisms and their evolution under ultra-low radiation backgrounds. Such studies have practical implications for radiation protection and medicine. Researchers from radiobiology and medicine will find new research opportunities once such an underground facility is established. The growing interest in this field of underground radiobiology is evidenced by several international projects which have been started recently. A large-scale discussion among Indian biologists is still to be initiated.

6. Overall infrastructure:

Taking into account the requirements of the proposals mentioned above, the underground facility may be envisaged to consist of

- One large cavern of 100 m (L) x 25 m (W) x 30 m (H)
- Multiple caverns, typically of the size 30-50m (L) x 20 m (W) x 15m (H) for various experiments
- Some of the experiments may require clean rooms of class 100- 1000
- Projected power: ~5 MW (3 MW for the large cavern, 2 MW for the smaller caverns combined)
- Projected water consumption for cooling of instruments: ~400 KLD
- Radon-free circulation system
- Additional space for basic amenities, services and auxiliary systems

7. Conclusions

The deliberations in this meeting brought forth the strong interest of the Indian scientific community across a broad range of disciplines to pursue a variety of challenging science problems, which can only be addressed in an underground facility. It would open up doors to perform new kinds of experiments, and hence would add a new dimension to the national scientific programme. There are already well-progressed indigenous projects that are waiting for such a facility, and the availability of such a facility will enable the scientific community to conceive of projects that could not be imagined earlier. For successful implementation of these ambitious scientific proposals the industry participation is essential, which will further the development of advanced technology in the country. Moreover, an underground facility is a long-term investment, and should provide sustained support to the science programmes over decades. In addition, there would be opportunities for international collaboration in the proposed projects, and for hosting of international experiments at such a facility.

Such a facility would need dedicated trained staff with specialized expertise for maintaining and operating underground facilities. It is therefore essential to create a pool of trained scientific and technical personnel for operation and maintenance of the world class underground facility over a prolonged period of a couple of decades or more. The underground science community in India would need to develop a coordinated roadmap for this purpose. The roadmap should include periodic workshops, summer/winter schools, training sessions, and other networking opportunities for scientists and engineers interested in underground experiments.

In summary, the attendees- including several young researchers, strongly endorse the need for a multi-cavern laboratory in India and are confident of developing a world class facility for ambitious scientific opportunities.

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