Future underground large detectors: prospects and physics case

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Abstract. A new generation of large underground detectors is being planned to further investigate neutrino mass and mixing and to search for possible CP violation that may provide a hint to the origin of our asymmetric universe. Such detectors would also investigate neutrinos in nature - from the earth’s crust to supernovae. The physics case for such a program is presented and plans for detectors worldwide are summarized.

1. Introduction
Underground physics for the next several decades involves a very wide range of topics. “Natural” sources of neutrinos under study include geoneutrinos, solar, supernova, atmospheric and cosmic neutrinos; proton decay is another potential new physics signal of natural origin. Artificial sources of neutrinos include radioactive sources, reactor neutrinos, stopped pion sources, superbeams, beta beams and neutrino factories. The detected events involve a range of energy scales spanning many orders of magnitude— from keV to TeV and beyond. A number of programs involving multi-kton detectors to further study of these topics are under consideration worldwide.

2. Detector Categories
There are three main kinds of detector technology under consideration for the next generation of multi-kton detectors: water Cherenkov, liquid argon and liquid scintillator. The capabilities of each for addressing different physics topics are described below.

2.1. Water Cherenkov Detectors
Water Cherenkov detectors, in the form of large volumes of ultrapure water surrounded by photomultiplier tubes (PMTs), are sensitive to the charged particles produced by interactions of neutrinos with energies greater than a few MeV. Charged particles moving faster than the speed of light in a medium produce Cherenkov photons if $\beta > 1/n$, where $n$ is the refractive index of the medium. Water is a convenient and cheap detector material, suitable for neutrino detection because very large volumes can be deployed cheaply, even though light yields are typically much lower than for scintillator. With index of refraction $n \sim 1.34$, the (total energy) Cherenkov threshold for electrons is 0.8 MeV; for muons the threshold is 160 MeV and for protons it is 1400 MeV. Energy loss is proportional to the number of photons detected, and it’s possible to reconstruct the charged particle’s interaction vertex and direction via the Cherenkov ring pattern (which has angle of 42° for relativistic particles). However it is important to remember that
heavy particles may be invisible in Cherenkov detectors, and signals from low energy electrons, positrons and gammas (which are detected via Compton-scattered electrons) may be lost.

Both low (few to few tens of MeV) and high (≥ GeV) neutrino detection are possible in large water Cherenkov detectors. In Cherenkov detectors, particle direction information is available using the angular information from the Cherenkov ring. This is helpful both for reconstructing multiple particles in high energy interactions, and for reconstructing neutrino-electron elastic scattering events at low energy. Particle type can be determined by evaluating the “fuzziness” of a track: electrons and gammas scatter and shower, whereas muons and pions have sharp tracks; Cherenkov angle can also be of use for particle identification. Low energy event detection may potentially be enhanced in water using Gd-doping [1], for which neutrons are captured on gadolinium nuclei, producing a cascade of gammas with ∼4 MeV visible energy; this allows tagging of interactions which produce neutrons, such as inverse beta decay.

Past water Cherenkov detectors include IMB [2] and Kamiokande [3]. The successful use of the technology for a wide range of physics topics is well proven at the few-tens-of-kton scale: Super-Kamiokande [4] has been running for fifteen years and has demonstrated a broad range of physics capability over several orders of magnitude in energy. Planned next-generation water Cherenkov detectors include one for the Long Baseline Neutrino Experiment (LBNE) in the U.S. [5], Hyper-Kamiokande [6] in Japan and MEMPHYS [7] in Europe. Pros and cons of large water Cherenkov detectors are summarized below.

| WATER CHERENKOV PROS | WATER CHERENKOV CONS |
|----------------------|----------------------|
| • Cheap material; can make very large | • Low light yield |
| • Proven at multi-kton scale | • Cherenkov threshold limits reconstruction |
| • Angular information from Cherenkov ring | • Thresholds at least ∼few MeV |
| • Some low energy physics reach | • Photosensors, large cavity costly |
| • Potential enhancement with Gd doping | |

2.2. Liquid Argon Time Projection Chambers
Liquid argon time projection chambers do not suffer from the Cherenkov threshold issue, and in principle extremely high quality particle reconstruction is possible. The ionization charge from the passage of particles through argon is drifted with an electric field and collected on readout wire planes; a 3D track can be reconstructed using charge arrival time information. Furthermore scintillation light signals in argon detected by photomultiplier tubes can allow fast timing of signals and enhance event localization. Very high purity cryogenic argon is required. Track granularity is determined by wire spacing, and in principle very fine-grained tracking can be achieved. Particle identification is possible by measuring ionization energy loss along a track.

Because of the excellent, full-particle tracking capability of liquid argon, very high-efficiency particle reconstruction allows a smaller LAr detector to match the efficiency of a water detector of a given mass. In principle, low energy physics (< 100 MeV, e.g. supernova neutrinos) is possible in LAr as well, assuming adequate triggering capability.

The current largest liquid argon detector instance is ICARUS [8] in Europe. In the U.S., a program of development towards large liquid argon detectors began with ArgoNeuT [9] at Fermilab and continues with MicroBooNE [10]. Further future possibilities include a future LAr detector for LBNE [5], GLACIER [11] in Europe, and detectors in Japan [12].

Although LAr is extremely promising and great progress is being made, the LAr technique is as yet unproven at multi-kton scale. Among the concerns are the safety issues associated with large quantities of cryogenic liquid, especially underground. Pros and cons of liquid argon are summarized below.
2.3. Liquid Scintillator Detectors

Liquid scintillator detectors consist of large volumes of clear hydrocarbon, in a homogeneous or segmented volume viewed by photomultiplier tubes. Light yield can be very high– typically 50 times more light per energy loss than Cherenkov detectors. This enables both low energy thresholds and good energy resolution. However, in order to detect neutrinos at low energy, extremely good radioactive purity is also required. Particle energy loss is proportional to number of photoelectrons detected, and particle interaction vertices can be reconstructed by timing; to a lesser extent direction and other properties can be reconstructed. Unfortunately because of the isotropy of scintillation light, directionality and tracking capabilities are relatively weak. Nevertheless, some high-energy particle reconstruction may be possible (e.g. [13]) using photon timing.

There is a long history of successful kton-scale scintillation detectors, starting with the segmented Baksan [14], MACRO [15] and LVD [16] detectors, and followed by KamLAND [17] and Borexino [18]. The near-future SNO+ [19] will be next. Proposed large future detectors include HanoHano [20] and LENA [21]. Pros and cons of liquid scintillator detectors are summarized below.

**SCINTILLATOR PROS**

- High light yield
- Low energy threshold
- Good energy resolution
- Some high energy reconstruction may be possible
- Significant experience at ~kton scale

**SCINTILLATOR CONS**

- Relatively expensive material
- High energy reconstruction difficult
- Stringent radioactive background requirements
- Photosensors and excavation may be costly

Table 1 lists past and current instances of large underground detectors [22].

3. International Programs

At the time of this writing there are future underground physics programs involving large detectors planned for the United States, Europe and Asia.

In the United States, LBNE is a planned program involving a new beam from Fermilab to an underground site 1300 km away at the Homestake mine in South Dakota [5]. The scenario under consideration is a new 700 kW beam in combination with a 200 kton fiducial mass water Cherenkov detector located at 4850 ft depth, with 12-inch high-quantum efficiency PMTs (a coverage similar to Super-K II) or two 17 kton liquid argon TPC detectors at 800 ft depth (or possibly at the deep site). A decision between these two technologies will be made at the end of 2011. In longer term, the LBNE far site could be irradiated by the 2 MW “Project X” beam [23] under development at Fermilab.

In Asia, a large water Cherenkov detector called Hyper-Kamiokande is being considered, for siting near the Super-K detector [6]. Two sites in the Tochibora mine (1500-1750 mwe depth)
Table 1. Summary of past and current large scintillator, liquid argon, and water Cherenkov detectors.

| Detector   | Location | Fiducial Mass (kton) | PMTs (diameter, cm) | Effective coverage | pe/MeV | Live dates  |
|------------|----------|----------------------|---------------------|--------------------|--------|-------------|
| Baksan     | Russia   | 0.33 (scint.)        | 3150 (15)           | segmented          | 40     | 1980–       |
| MACRO      | Italy    | 0.6 (scint.)         | 476 (20)            | segmented          | 18     | 1989–2000   |
| LVD        | Italy    | 1 (scint.)           | 840 (15)            | segmented          | 15     | 1992–       |
| KamLAND    | Japan    | 1 (scint.)           | 1325 (43)           | 34%                | 460    | 2002–       |
|            |          |                      |                     |                    |        |             |
| Borexino   | Italy    | 0.1 (scint.)         | 2212 (20)           | 30%                | 500    | 2005–       |
| ICARUS     | Italy    | 0.76 (LAr)           | -                   | -                  | -      | 2010–       |
| IMB-1      | US       | 3.3 (H₂O)            | 2048 (12.5)         | 1%                 | 0.25   | 1982-1985   |
| IMB-2      | US       | 3.3 (H₂O)            | 2048 (20)           | 4.5%               | 1.1    | 1987-1990   |
| Kamiokande I | Japan | 0.88 (H₂O)          | 1000/948 (50)      | 20%                | 3.4    | 1983-1985   |
| Kamiokande II | Japan | 1.04 (H₂O)         | 1000/948 (50)      | 20%                | 3.4    | 1986-1990+  |
| Kamiokande III | Japan | 1.04 (H₂O)         | 1000/948 (50)      | 20%                | 3.4    | 1990-1995   |
| Super-K I  | Japan    | 22.5 (H₂O)          | 11146 (50)         | 39%                | 6      | 1996-2001   |
| Super-K II | Japan    | 22.5 (H₂O)          | 5182 (50)          | 19%                | 3      | 2002-2005   |
| Super-K III+ | Japan | 22.5 (H₂O)         | 11129 (50)         | 39%                | 6      | 2006-       |
| SNO        | Canada   | 1 (D₂O)              | 9438 (20)           | 54%                | 9      | 1999-2006   |

are under study. The proposed detector has a fiducial mass of 540 kton and 10-20% Super-K-equivalent photomultiplier coverage. The plan is for an eventual upgrade of the T2K beam to 1.7 MW. There are also ideas for Japan-based liquid argon detectors, including a 100 kton facility at Okinoshima island halfway between Japan and Korea [12].

In Europe, a number of detector and siting possibilities are being explored as part of the LAGUNA program [24]. Under consideration are a 0.5 Mt water Cherenkov detector (MEMPHYS [7]), a 100 kt LAr detector (GLACIER [11]) and a 50 kton scintillator detector (LENA [21]). Beam options from CERN include superbeams, and perhaps beta beams or neutrino factory in the farther future. Top sites under consideration are Pyhäsalmi in Finland (2300 km from CERN), Fréjus (130 km from CERN) and Umbria (665 km from CERN, off-axis from the existing CNGS beam).

4. Physics Overview

Underground physics topics that I will discuss here fall in two main categories, for which the detector challenges are different. At ~GeV energies, the main experimental issue is efficient multi-particle reconstruction. The physics topics at high energy include long baseline neutrinos, atmospheric neutrinos and proton decay. For these, one must be able to separate, identify and measure the energies of the various particles in an event, in order to have high signal efficiency and good background rejection. At low energy, in the few to few tens of MeV range, the experimental issues are light or charge collection, and radioactive background reduction. Low energy physics topics include burst supernova neutrinos, diffuse supernova neutrino background and geoneutrinos.
4.1. Neutrino Oscillations with Beams

As mentioned previously, several programs worldwide are working towards long baseline oscillation studies.

Our model of neutrino mixing requires a $3 \times 3$ mixing matrix, and the oscillation is described by a total of six parameters, of which four are well known. Three mixing angles and a CP-violating phase are present in the PMNS (Pontecorvo-Maki-Nakagawa-Sakata) matrix: only two of the mixing angles are known (for the third, $\theta_{13}$, there are indications of a non-zero value from T2K [25], MINOS [26] and Double CHOOZ [27]). The mixing matrix can be written out as a product of three “Euler-like” rotations:

$$
U = \begin{pmatrix}
1 & 0 & 0 \\
0 & c_{23} & s_{23} \\
0 & -s_{23} & c_{23}
\end{pmatrix}
\begin{pmatrix}
c_{13} & 0 & s_{13}e^{-i\delta} \\
0 & 1 & 0 \\
-s_{13}e^{i\delta} & 0 & c_{13}
\end{pmatrix}
\begin{pmatrix}
c_{12} & s_{12} & 0 \\
-s_{12} & c_{12} & 0 \\
0 & 0 & 1
\end{pmatrix}
$$

where “$s$” represents sine of the mixing angle and “$c$” represents cosine. The “1-2” matrix describes “solar” mixing; the “2-3” matrix describes “atmospheric” mixing. The CP-violating phase $\delta$ is unknown.\(^1\) Another unknown is the absolute mass scale, since oscillation measurements inform us only on mass differences. Although two of the mass-squared differences are known, we do not know how the three masses are arranged: there could be two light ones and a heavy one (the “normal” hierarchy) or two heavy ones and a light one (the “inverted” hierarchy).

While the current cohort of oscillation experiments is pursuing the measurement of $\theta_{13}$, the long-term goal is to observe CP violation in the lepton sector. CP violation can be parameterized by a complex phase $\delta$ in the PMNS mixing matrix, and information may be extracted from measurements of the transition probabilities for neutrinos and antineutrinos, e.g. $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ [28]. However extraction of information about $\delta$ from these observables is not completely straightforward, because transition rates depend on all of the PMNS parameters; furthermore, matter effects come into play. One needs precision measurements of all parameters, and multiple measurements, if possible including both neutrinos and antineutrinos, to resolve all ambiguities (see e.g. [29, 30, 31]). Matter effects in particular can be considered both a help and a hindrance: they cause a matter-dependent asymmetry in transition rates between neutrinos and antineutrinos, which can mask CP violation. However the sign of the modification depends on the hierarchy: therefore long baseline oscillation measurements can distinguish between normal and inverted hierarchies.

The primary detectors choices for long baseline oscillation experiments are water Cherenkov and liquid argon, although recent work has shown some capability for event reconstruction in scintillator [13]. Approximately six times the mass is required for a water detector of equivalent sensitivity to a given mass of liquid argon, because of the better efficiency in principle achievable in liquid argon.

A different approach to CP violation, involving a large Gd-doped water detector, is the DAEδALUS idea [32]. In this approach the neutrino sources are cyclotrons producing stopped-pion neutrinos (of $\sim 30$ MeV energies) at baselines from 1.5 km to 20 km. There are no matter effects for this setup; the approach is complementary to conventional long baseline beams.

4.2. Atmospheric Neutrinos

The first unambiguous evidence of neutrino oscillations came from atmospheric neutrinos [33], and future large detectors will continue to exploit this neutrino source for physics. Information on CP violation and mass hierarchy is present in the energy and angle distributions. Detector issues are similar as for long baseline neutrinos: one needs good disentanglement of the particles

\(^1\) There are also “Majorana phases”, which do not affect oscillation probabilities.
in a high energy interaction, as well as high statistics [5]. Although not in one of the three categories listed here, a planned future underground large detector optimized for atmospheric neutrinos is the planned 50-kton ICAL iron calorimeter detector for the India-based Neutrino Observatory [34, 35]. This detector has lepton sign-selection capability using a magnetic field to enable separation of neutrinos and antineutrinos.

4.3. Proton Decay
A final high-energy topic is proton decay, which was in fact the original motivator for construction of large underground detectors. Baryon number violation is the “smoking gun” for Grand Unified Theories; heavy bosons predicted by these theories mediate transitions between quarks and leptons and cause baryon number-violating decays. The experimental signature is a \( \sim \)GeV event with products and kinematics specific to the decay mode. The “golden” baryon-number-violating decay mode is \( e^+\pi^0 \), but there are various modes with varying theoretical motivations. Super-K currently dominates the limits [36]. However, for some modes, such as \( \nu K \) modes which are SUSY-motivated, efficiency in water is relatively poor [37]. For these, LAr detectors would have better sensitivity due to finer-grained tracking and lack of Cherenkov threshold [5]. For some baryon-number-violating modes, scintillator may also do quite well. For example, LENA may be able to detect kaon decays via a distinctive timing signature [38].

4.4. Supernova burst neutrinos
Going lower in energy, supernova burst neutrinos occupy the few tens of MeV regime. A core collapse supernova will produce a burst of neutrinos of all flavors with energies up to about 50 MeV, over a period of a few tens of seconds. Reference [39] and references therein give an overview of supernova neutrino detection; reference [40] is a recent summary of what may be learned from the observation of a supernova neutrino burst. So far the only supernova neutrino observation is from SN1987A [41, 42, 43, 44]. We expect enormously enhanced information from the next nearby observation. A core collapse burst is expected in the Milky Way approximately every 30 years.

All large detector types would observe copious neutrinos, although the flavor sensitivity depends on the target. In particular, both water and scintillator will observe nearly-pure \( \bar{\nu}_e \) signals, via inverse beta decay on protons. In contrast, liquid argon detectors have excellent sensitivity to \( \nu_e \) via CC absorption on argon. The signals are complementary and diverse worldwide flavor sensitivity is best for extracting the most physics and astrophysics from a supernova burst signal [5].

4.5. Diffuse supernova neutrino background
While supernova burst neutrinos will provide enormous information, a core collapse near enough to observe occurs only a few times per century. However, we are awash in a sea of “relic” or diffuse supernova neutrinos from supernovae that have gone off since the Universe began (the Diffuse Supernova Neutrino Background, or DSNB) [45, 46]. Observation of the DSNB will help understand typical supernova neutrino emission. Because DSNB neutrinos will be observed as singles without any accompanying optical event, the difficulty for measurement is tagging signal against background. Nevertheless there is a window between about 15 and 40 MeV, bounded by solar neutrino background at low energy and atmospheric neutrino background at high energy. The best limits on the DSNB flux currently come from Super-K [47]. A promising possibility is to enhance signal to background in water with Gd-tagging [1, 5]; scintillator may also do well (although is vulnerable to atmospheric background) [21]. Argon is sensitive to the \( \nu_e \) relic flux, although backgrounds are less well understood [48].
4.6. Geoneutrinos

Going yet lower in energy: geoneutrinos are emitted from radioactive decays in the Earth’s mantle and crust. At present it is unknown how much of Earth’s heat comes from radioactive decay, and measurement of geoneutrinos may help to constrain models. There have been recent measurements from KamLAND [49] and Borexino [50]. Future scintillator experiments hold significant promise for improving knowledge, thanks to low threshold and good energy resolution. Reactor neutrino background is the biggest issue, so siting of new detectors will be important for this physics topic. Pyhäsimi in Finland is a promising site [21].

Table 2 summarizes the capabilities of the three detector technologies for the physics topics selected for this review. A detector sited at depth is required for all of these physics topics except long baseline oscillations.

| Physics topic                  | Water                  | Liquid argon                      | Scintillator                      |
|--------------------------------|------------------------|----------------------------------|----------------------------------|
| Long baseline oscillations     | Yes, proven            | Yes, good efficiency             | Some reconstruction may be possible |
| Nucleon decay                  | Yes, esp. $l^{+}\pi^{0}$ modes | Yes, $K\nu$                      | Yes, $K\nu$                      |
| Atmospheric neutrinos          | Yes, huge statistics   | Yes, fine-grained reconstruction  | Possibly                          |
| Supernova burst neutrinos      | Yes, $\bar{\nu}_e$, huge statistics, pointing | Yes, $\nu_e$                    | Yes, $\bar{\nu}_e$, + tagged NC, good statistics |
| DSNB                           | Yes, with Gd           | $\nu_e$, unknown bg              | Possibly, unknown bg             |
| Geoneutrinos                   | No                     | No                               | Yes                              |

For lack of space, I am omitting here a number of other interesting topics in particle physics and particle astrophysics that can be done with large underground detectors. These include solar neutrinos, reactor neutrinos, short baseline oscillations with radioactive sources, neutrinoless double beta decay searches (by dissolving double beta decay candidate isotopes in water or scintillator and looking for spectral signatures), indirect WIMP dark matter searches, cosmic neutrino searches and exotic particle searches. One should also not ignore the possibility for unexpected discoveries, beyond the original imagined scope of the physics program: indeed, neutrino oscillation was discovered by a detector originally intended to find proton decay, and geoneutrinos were detected in reactor and solar neutrino experiments. Any of the three large detector technologies considered here has excellent breadth for covering diverse physics topics.

5. Summary

In summary, there is a wide array of physics opportunities for water Cherenkov, liquid argon and scintillator detectors underground. A broad global program is highly desirable.

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