PROCEEDINGS OF SCIENCE

Deep Underground Laboratories - Multidisciplinary Research

Yeongduk Kim[a,*]

[a] *Institute for Basic Science,*
55 Expo-ro, Daejeon, South Korea

E-mail: ydkim@ibs.re.kr

This article describes the status of world underground laboratories. The experiments for dark matter searches and neutrino double beta decay continually increase the diversity and size of the experiments. In addition, neutrino oscillation experiments using large water Cherenkov and liquid scintillator detectors enter new generation stages. Therefore, the underground laboratories are expanding rapidly in total area and space. At the same time, the background level requirements get more stringent, and the techniques for the assay and mitigation of ultra-low radioactivity develop. In addition to the astrophysics program, I briefly described the recent multidisciplinary research at the underground laboratories.

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*Speaker

PoS(TAUP2023)298

1. Overview of underground laboratories

Underground laboratories have been built to search for rare events expected from the direct interaction of dark matter and rare decay processes, including the neutrinoless double beta decays, neutrino interactions, etc. New underground laboratories are being constructed, expanding the whole space capacity and deepening the depth. Recently, new underground laboratories have been built mainly in Asia: JUNO and CJPL-II in China, Hyper-K in Japan, SUPL in Australia, and Yemilab in Korea. JUNO and Hyper-K underground laboratories are under construction to install large liquid detectors for neutrino oscillations from reactors and accelerators. CJPL-II is a newly constructed laboratory with ample space underground in China's deepest location.

Figure 1: Overview of underground facilities located worldwide, showing various key characteristics in-depth and underground laboratory capacity. Slide from Jaret Heise (SURF) at the TUAP23 conference.

2. Radiopurity for ultra-low background reduction

For the ultimate backgrounds required for next-generation experiments underground, we need to improve both the assay of the materials and the mitigation of the background sources. For the radioassay of the materials, we need to measure the materials' lower radioactivity since the experiments' requirements get more stringent. For mitigation, we need to develop new techniques for shielding and actively removing the sources, etc.

2.1 Radioassay

The leading equipment for radioassay of the materials at underground laboratories are ICP-MS and HPGe detectors. ICP-MS can be on the ground, but HPGe detectors for ultra-low radioactivity should be underground. The potential inequilibrium in the radioactivities of U and Th sequential decays in the material should be considered so that the HPGe measurement of ^{228}Ac, ^{228}Th, and ^{226}Ra in addition to the ICP-MS measurements are desirable.

HPGe detectors measure the gamma rays from the decays of ^{226}Ra, ^{228}Ra, and ^{40}K, etc. The most sensitive HPGe detector is the GeMPI at the Gran Sasso underground laboratory, of which the sensitivity is about 10 μBq/kg. Over 100 HPGe detectors are installed underground, and the number is increasing. The HPGe detector facilities housing over 10 HPGe detectors, such as BUGS(Boulby), BHUC(SURF), DURF(CJPL), and STELLA(LNGS) are recently constructed. Recently, multi HPGe crystal detectors have been made; for example, 14 HPGe crystals at the top and bottom of the shielding measure a sample with high efficiency and large mass of sample [4]. This can improve the sensitivity of the radioassay of gamma rays less than 100 μBq/kg for heavy samples. 4 HPGe crystal array is also under construction at CJPL-II and STELLA facility of LNGS.

Surface contamination is one of the most hazardous sources to ultra-low background experiments. The long-lived ^{226}Ra, ^{228}Ra, and ^{210}Pb, in addition to ^{238}U and ^{232}Th, can contaminate the surface of the detector components and shieldings. One of the most sensitive alpha counters dedicated to surface contamination measurement is UltraLo-1800 by Xia company. This alpha counter can measure alphas from the sample surface separately from the detector surface and has lower backgrounds at the underground than at the ground. More alpha counters have been installed in underground laboratories recently. This instrument can be sensitive down to the level of 10^{-4}alphas/(cm^{2}hour) though it has a limit of the thickness of the sample less than about 8 mm. The bulk alphas can be separated from the surface alphas by the energy of the alphas.

ICP-MS measures the primordial isotopes of ^{238}U and ^{232}Th. The sensitivities of ICP-MS machines have improved over the last few years. They can be down to 0.01 ppt level coupled with solid phase extraction techniques. More advanced equipment, such as HR ICP-MS (LNGS) and QQQ-ICP-MS (PNNL, LSC), are installed. More underground laboratories, Kamioka Observatory, SNOLAB, CUP, and CJPL, have dedicated ISP-MS machines for stable measurements.

Radon emanation from construction materials is critical to dark matter searches. The radon emanation chamber as large as 300 L has been made, and measurement sensitivity reaches 0.2 mBq. Facilities for radon emanation have been installed at Boulby, SNOLAB, and SURF underground labs.

Accelerator Mass Spectrometry (AMS) is another sensitive detection system for mother nuclei. With an accelerated atomic nucleus, we can more easily separate the mass by the spectrometer. It can be sensitive down to 1 mBq/kg for ^{210}Pb nuclei [7].

If some material is required to be measured below 10μBq/kg, then we have to combine the technologies we have. Measurement of the radioactivity level less than 0.1 ppt for ^{238}U and ^{232}Th in electroformed copper was reported by ICP-MS measurement with concentration [8]. We can do the solid phase extraction of Radium with more than 1 kg of a sample. Then, we can measure the decay of the Radium isotopes, ^{226}Ra or ^{228}Ra. The extracted material can be measured with a low-temperature calorimetric detector or liquid scintillator with alpha separation power. Or the material can be measured with a well-type HPGe detector for gamma rays of Radium decay.

A raiopurity database has been jointly maintained by PNNL and SNOLAB (https://radiopurity.org). The current focus continues to be the robustness of the system, feature support, and encouraging the addition of assay data for the community [6].

2.2 Mitigation of the radioactivity

With the ultra-low radioassay measurements, we must develop techniques to mitigate the radioactivity lower than the experimental requirements. The radon-free air-supplying system is one of the most essential apparatus, which usually has a capacity of a few hundred m^3/hour and a radon reduction factor larger than 5000.

In addition, we need a clean room with a dust-free facility with a certain level of cleanliness since dust is one of the most common and hazardous sources of radioactivity. Dust fall-out has been measured directly with and without the clean room environment, and the class 2000 clean room has two orders of magnitude lower fall-out than a room without a clean room facility operating[5]. Therefore, the demand for dust-free space unground is increasing. Some experiments need CLASS 10, which is quite challenging to maintain. The CLASS 1000 is most required, and the requirement for Radon reduced (< 20 Bq/m^3) clean room is also increasing [3].

The facility for electroforming copper has been constructed at SURF underground, LSC, andinLAB (ECuME). At LNGS, a new material manufacturing facility, HAMMER, based on metal 3D printing, has been established. The raw material for HAMMER can be electroformed copper, which is expected to produce very pure copper. Chemical purification techniques, re-crystallization, ion exchange, distillation, etc., are developed for pure crystal production and background reduction.

The detectors from environmental backgrounds adopt more homogeneous shielding, such as tanks with water, liquid scintillators, liquid argon, and liquid nitrogen (LN2). A large LN2 tank of 2000 m^3 has been constructed at CJPL-II for the CDEX experiment.

3. Multidisciplinary research

As underground laboratories develop and expand, other branches of sciences, such as biology, geology, nuclear astrophysics, and radiation science, are emerging as research activities at deep underground [9]. We could call this research multidisciplinary research. First, nuclear astrophysics underground has developed since the first low energy accelerator, LUNA, was installed at Gran Sasso laboratory in 2001. Since then, CASPAR at SURF, JUNA at CJPL-II, and Felsenkeller accelerators have been installed. In particular, Felsenkeller is a shallow-depth underground laboratory that can still take advantage of being underground to reduce the background. There has been big progress in the precision of the data with the threshold lower than the experiments at ground [10]. Underground measurements led to unprecedented precision in measuring key reaction cross-sections and breakthroughs in our understanding of the inner workings of stars. A few of the seminal measurements are ^{2}H$(\alpha,\gamma)^{6}$Li, ^{3}He(^{3}He, 2p)^{4}He, ^{14}N(p, γ)^{15}O, ^{15}N(p, γ)^{16}O, ^{17}O(p, γ)^{18}F etc [10]. Table 1 shows the energy and current of the underground accelerators.

Table 1: Underground accelerators for nuclear astrophysics research.

Facility	Location	Began	Depth mwe	Accelerator	Energy keV	Intensity Proton, α
LUNA-400	LNGS	2001	3800	Cockcroft-Walton	400	1mA, 0.5mA
LUNA-MV	LNGS	2022	3800	Cockcroft-Walton	3500	1mA, 0.5mA
CASPAR	SURF	2017	4300	Van de Graaff	1100	0.25mA
JUNA	CJPL	2020	7620		400	12 emA, 6 emA
Felsenkeller	Felsenkeller	2019	110	Pelletron Tandem	5000	0.01mA

PoS(TAUP2023)298

Biology underground can be categorized into two fields. First, the underground microbial research unveiled that more than 99 % of microbes in nature are unknown. Huge microbial diversity in extreme conditions, such as deep underground, is to be discovered. The second field of biology underground is on the low radiation background effect on living systems. One of the research investigates the long-term impact of low-dose radiation on various types of living systems [12, 13] Underground laboratories, LNGS, SURF, Boulby, LSC, LSM, and SNOLAB have reported to have dedicated biology program.

The semiconductor industry, and more recently, quantum computing, is another field active at underground. To make quantum computing viable, the qubits must exhibit long coherence times. An excess density of quasi-particles can spoil coherence for supercomputing qubits. One contribution to quasi-particle poisoning appears to be ionizing background radiation. Deep underground laboratories can be a suitable environment for this study [11]. We expect more tests underground for qubit coherence time in various laboratories.

4. Updates on underground laboratories

Here are some new developments at each underground laboratory. The lists are not intended to be complete.

1. **LNGS**: STELLA facility for HPGe detectors is constructed. New GeMPI detectors will be installed. NOA, a new large clean room with an Rn-free air supply, is constructed. The area is 420 m^2 with a volume of 1400 m^3. DarkSide-20k detector components will be assembled in NOA. A cryogenic platform with two dilution refrigerators to test cryogenic detectors will be installed.
2. **CJPL**: DURF (Deep Underground and ultra-low Radiation background Facility) project will be finished by the end of 2024 inside the CJPL-II laboratory. 15 HPGe detectors with low Radon air purging will be installed. A large LN2 tank (13m diameter and height) and a water tank for detector shielding are constructed. The pit for a 500-ton neutrino detector is prepared.
3. **SURF** : The DUNE cavities are 77 % finished by volume. After the DUNE experimental halls are constructed, two new caverns (100m x 20m x 24m) will be constructed and operational in about 2030. A radioassay facility, BHUC, has 6 HPGe detectors under operation.
4. **SNOLAB**: The background, radon, neutrons, and gammas are routinely measured. CUTE (shielded dilution refrigerator) has operated since 2020, and SuperCDMS detectors are tested. Low background lab including 6 HPGe detectors and alpha counters has been constructed. A liquid nitrogen generator with a production capability of about 300 L / day began operation.
5. **Kamioka, HK** : Super-K detector is loaded with 0.03% Gd and first data is released. Hyper-Kamiokande detector dome and cavern for the water purification system have been excavated. The excavation will be completed in 2024.
6. **Boulby Laboratory** : A clean room of 4000 m^3 with 3 Bq/m^3 has been established. BUGS is a material screening facility with 8 ULB HPGe detectors, 2 XIA alpha counters, and Radon emanation measurement equipment. A diverse multidisciplinary program, muon

tomography, mining and extraplanetary exploration instrumentation development (MINAR), and astrobiology (BISAL) programs are ongoing.

7. **LSM** : Many test experiments are going on. SuperNEMO double beta experiment is under installation. More than 20 HPGe detectors are installed for industrial usage.
8. **LSC** : GeRysy, an ultra-pure germanium detector, has been operating inside a removable clean tent and a new ICPMS-QQQ is placed in a clean room underground.
9. **Yemilab** : A new underground lab at 1000 m depth is constructed and operational in 2022. A class 100 clean room and a radon-free air supply system are installed for a double beta decay experiment, AMoRE. A pit for a kiloton liquid scintillator detector is made.
10. **PAUL** : The first underground laboratory in Africa is planned at a tunnel near Cape Town. The overburden is 800 meters, and the laboratory area would be about 600 m^2.

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