Radioassay and Purification for Experiments at Y2L and Yemilab in Korea

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Abstract. Two major rare-process search experiments, COSINE-100 for WIMP dark matter and AMoRE for neutrinoless double beta decay, have been running at the Yangyang underground laboratory (Y2L) in Korea for about four years. In order to measure radio-activities of materials in both experiments, a number of ultra-low radioactivity measurement detectors have been developed and are now operational. For radioassays of raw materials and detector components, an ICP-MS, an argon gas ionization counter, and a number of HPGe detectors are being used. Three silicon PIN diode-based radon chamber detectors have been either upgraded or constructed for accurate measurements of atmospheric radon in a radon reduction system. A fourteen element HPGe detectors array was installed in 2016 for more sensitive measurements and larger sample capacities than those could be tested in two single crystal HPGe detectors. Since the Y2L space is too small to accommodate the next phases of both experiments, a new underground laboratory, called Yemilab, is being constructed in Jeongseon, Korea with a factor of ten more space (~2,800 m²) and a ~1,100 m overburden compared to ~200 m² and ~700 m at Y2L. The future experiments require detector materials with substantially lower background levels than those in the current ones. Various types of scintillating crystals such as CaMoO₄, Li₂MoO₄, and NaI(Tl) are being grown with purification methods specifically developed for the raw materials. A summary on radioassay and purification results for experiments at Y2L and Yemilab in Korea will be presented.

1. Introduction
The Center for Underground Physics (CUP) started in mid 2013 as one of the centers of the Institute for Basic Science (IBS) in Korea. CUP has been successfully running two major experiments for the last four years in Y2L with an overburden of ~700 m, where the KIMS (Korean Invisible Matter Search) experiment operated from 2003 to 2012 [1]. The two experiments are searching for rare-processes such as WIMP dark matter using NaI(Tl) crystals (COSINE-100) and neutrinoless double beta decay using molybdate (¹⁰⁰Mo) crystals (AMoRE) [2,3].

The rare-process search experiments require ultra-low radioactive background levels in materials comprising the detectors themselves and in the outside shielding materials. In order to prepare radiopure components, all the raw materials for the detectors and shields are screened by extremely sensitive radioassay devices. In addition, the raw materials for the crystal growth such as NaI and MoO₃ powders have to be purified because commercially available powders are not pure enough for the experiments.
Most of the crystals are being grown in CUP as part of a program of R&D studies to control background levels internal to the crystals [5-7].

CUP has installed and operated the radioassay devices such as an argon gas ionization alpha counter [4] and HPGe (High Purity Germanium) detectors [8-11] in Y2L, an ICP-MS (Inductively Coupled Plasma - Mass Spectrometer, Agilent 7900) in the IBS HQ campus where CUP is located [5,6]. Three radon chamber detectors with volume of ~70L have been either upgraded or constructed to monitor the radon-free air from a radon reduction system running in the Y2L and for measurements of samples enclosed in a vacuum chamber [12].

Two early phases of the AMoRE experiment, AMoRE-Pilot and AMoRE-I with up to 18 crystals, use the same cryostat at Y2L. The next phase of the experiment, AMoRE-II, will have at least 200 crystals in a bigger cryostat with shielding structures that requires a larger space than that Y2L can accommodate. CUP has been constructing a new underground facility, called Yemilab, in Jeongseon, Korea since 2017. Yemilab, to be ready by 2021 for AMoRE-II construction, will have about 10 times more space and be deeper by about 400 m than Y2L.

2. Radioassay devices in Y2L

In order to measure ultra-low background materials, some radioassay devices have to be located in an underground location such as Y2L in order to reduce the cosmic radiation background.

An argon gas ionization alpha counter has been running from 2015 summer to study alphas from surfaces of raw materials, as shown in Fig. 1 (a). The alpha counter at Y2L has an order of magnitude higher sensitivity than the company specification for above-ground operation. By measuring surface contaminations by $^{210}$Pb, we could screen materials and study surface cleaning methods for different detector components.

Three HPGe detectors are installed and have been running together since 2017. Two 100% efficiency single detectors, shown in Fig. 1 (b) and (c), are screening raw materials for different projects as gamma spectrometers [14]. The measurement statistics of the two detector applications for different projects are summarized in Table 1.

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### Table 1. Number of samples measured in each HPGe detector for the last three years. The upper table is for CC1 and the bottom for CC2. For low background level samples, about 2-3 weeks of exposures are required.

| Year | Total | AMoRE | COSINE | HPGe | LZ | Y2L | Yemi | R&D |
|------|-------|-------|--------|------|----|-----|------|-----|
| 2017 | 15    | 9     | 2      | 3    | 1  |     |      |     |
| 2018 | 17    | 10    | 5      | 1    | 1  |     |      |     |
| 2019 | 6     | 4     | 1      | 1    | 1  |     |      |     |

| Year | Total | AMoRE | COSINE | HPGe | LZ | Y2L | Yemi | R&D |
|------|-------|-------|--------|------|----|-----|------|-----|
| 2017 | 21    | 7     | 11     | 3    |    |     |      |     |
| 2018 | 23    | 15    | 5      | 2    | 1  |     |      |     |
| 2019 | 11    | 7     | 1      | 2    | 1  |     |      |     |
3. ICP-MS and Radon chamber detectors

The ICP-MS machine, shown in Fig. 2 (a), is installed at IBS HQ together with the crystal growing and purification facilities. In addition to confirming purity levels in crystal related raw materials, detector components like copper for detector frame and Vikuiti film for light reflector are also measured with this machine quite accurately together with an extraction method developed at CUP.

A cylindrical radon chamber detector used for the KIMS experiment [15] was upgraded with a new silicon PIN Photo Diode (PD) sensor (Hamamatsu S3204-09) and a new preamplifier chip (Hamamtsu H4083). Two more radon chamber detectors with a round shaped bottom with a better electric field for collecting positively charged radon daughter particles were constructed with the same sensors and electronics. One of the two new detectors is used to monitor the radon-free air from the radon reduction system (RRS) in Y2L as shown in Fig. 2 (b). An energy distribution from a closed air measurement shows distinct alpha peaks from $^{218}$Po and $^{214}$Po decays as shown in Fig. 2 (c). The chamber detectors will be used for monitoring the RRS in Y2L and screening emanating gases from samples in a vacuum chamber.

![Fig. 2. An ICP-MS machine (Agilent 7900) (a), a radon chamber detector measuring radon-free air from the radon reduction system in Y2L (b), an energy distribution from radon chamber detector with two alpha peaks from $^{218}$Po and $^{214}$Po decays from radon daughters (c).](image)

4. Yemilab at Jeongseon, Korea

Since CUP was started in 2013, it was realized that a new underground facility with more space than Y2L was needed for the next phase experiments with bigger detectors, such as AMoRE-II with more than 200 kg of crystals. After intensive studies and visits to many mountain areas in South Korea, the Handeok mine (an active iron mine at Jeongseon) was selected as the site for a future underground laboratory. It has already a vertical shaft of ~600 m deep under the eponymous Mt. Yemi. The underground laboratory will be located ~700 m from the bottom of the shaft, thereby providing a ~1,100 m overburden as shown in Fig. 3 (a). The construction of Yemilab including a personal cage for the shaft started from 2017 and the entrance tunnel is currently being excavated as shown in Fig. 3 (b); completion is expected by early 2020. The AMoRE experimental hall and tunnels are planned to be ready for experiments by mid 2021. The completed experimental halls and tunnels are shown in Fig. 3 (c) with a total space of ~2,800 m$^2$, which is more than 10 times that of Y2L.

5. Summary

CUP has prepared and successfully operates a number of radioassay devices in Y2L and IBS HQ for screening of raw materials for use in current and future rare process experiments. Sensitivities of those machines have been improved as we learn by experience and develop new methods.

Construction of the new Yemilab started in 2017 and has been going smoothly with the entrance tunnel excavation nearing completion at this time. It is planned to be completed by mid 2021 and be ready for future experiments with much bigger detectors compared to the ones now running at Y2L.
Fig. 3. A schematic of the newly built Yemilab in Handeok iron mine at Jeongseon, Korea (a), a photo of entrance tunnel excavation currently on-going (b), a schematic for completed experimental halls and tunnels in Yemilab (c).

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