An ultra-low radioactivity measurement facility at the Center for Underground Physics in Korea

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On behalf of CUP measurements groups

Center for underground Physics,
Institute for Basic Science, Korea
Yang Yang (Y2L) Underground Laboratory

Yang Yang Pumped Storage Power Plant

Center for Underground Physics

IBS (Institute for Basic Science)

Since 2003

KIMS/COSINE (Dark Matter Search)

AMoRE (Double Beta Decay Experiment)

Minimum depth: 700 m / Access to the lab by car (~2km)

Seoul

IBS

Y2L

IBS (Institute for Basic Science)
Detectors at the Y2L

- 3 HPGe detectors (2 Coax, 1 Well)
- 1 Array with 14 HPGe detectors
- Alpha ionization counter
- Radon chamber detector

~700 m deep
HPGe detectors

**CC1: 100% HPGe CANBERRA**

- Dedicated shielding:
- top & bottom 10 cm Pb + 10 cm Cu (inner)
- side 15 cm Pb + 10 cm Cu (inner)
- IMPROVED: 5 cm ancient lead near the detector

**Well type ORTEC**

110 cc of ACTIVE VOLUME

**CC2: 100% HPGe CANBERRA**

- A new installation with an improved new shielding

**CANBERRA 777 Ultra Low Background Shield**

- Outer 9.5 cm thick low carbon steel
- 15 cm of low background Pb
- 1.5 mm high purity low background copper
- Additional ~5 cm copper disks on the side and on top

**counts/day**

**Energy (keV)**

![Graph showing energy distribution](image)

![Image of ORTEC HPGe detector](image)
HPGe Array

• Developed in collaboration with CANBERRA,
• 2 ARRAYS placed one above the other with 7 HPGe (70% relative efficiency) each.
• Total detectors: 14 HPGe

• Improving the sensitivity is mandatory to reduce the intrinsic background

• Careful and accurate selection of O-rings
  – O-rings generally have high contamination in 40K
  – Our selection has very low contamination in Th and U: 16 ± 4 & 13 ± 4 mBq/kg respectively
• Aluminum has been replaced by copper everywhere considering the efficiency loss at low energies
  – End Cap & Holder surrounding the crystals are made of copper, machined as thin as possible for a total of 2 mm dead layer
SHIELDING

Main Structure from outside: **20cm Lead + 10cm Goslar Lead + 10cm Copper**

**Two doors** on the side can slide on rails using a motor system

- The top array should be lifted to place samples with different sizes.
- Specific tools are made to lift the dewar and the array together.
- A part of the shielding will also be lifted to prevent any damages on the cold finger
Lifting scheme

- Lifting 3 parts simultaneously
  - Top Array, Shielding, Dewar
  - Design of a Tool to lift the array
  - 2mm each step (cold finger “safe” stress)
- Adjustable spacers between the bars to fix the height
  - from 2.5 up to 5 cm
  - Support for samples
 Electronics & DAQ

- Shaping Amplifier CANBERRA 2026
  Shaping time 6 μs
- HV power supply ISEG NHS606
  6 channels, positive, programmable

- Flash Analog to Digital Converter
  - 500MS/s 12bit dynamic range 2.5V
  - 2 modules with 4 channels each
- Local trigger signals generated in the FADCs are sent to the Trigger Control Board (TCB)
- TCB will decide and generate a GLOBAL TRIGGER to be sent back to FADCs in 500ns via a LAN cable connection
- TCB synchronize the FADCs clocks and access to the FADCs register to send the information to PC
Energy Resolution & BKG runs

**BOTTOM ARRAY**

| Energy Resolution (keV) for 1332 keV $^{60}$Co |
|------------------|------------------|------------------|------------------|------------------|------------------|------------------|
| DET0             | DET1             | DET2             | DET3             | DET4             | DET5             | DET6             |
| 1.96             | 1.98             | X                | 3.16             | 2.22             | 1.83             | 2.10             |

**TOP ARRAY**

| Energy Resolution (keV) for 1332 keV $^{60}$Co |
|------------------|------------------|------------------|------------------|------------------|------------------|------------------|
| DET0             | DET1             | DET2             | DET3             | DET4             | DET5             | DET6             |
| 1.90             | 2.17             | X                | 1.93             | 1.36             | 1.95             | 1.85             |

**BKG spectra**

Red : w/o Radon free air, N2 gas flow (8.4 days)

Blue : with Radon free air (25.5 days)
The Ultra Low Background Facility

- 2 arrays of 7 HPGe detectors with 70% of relative efficiency designed for the detection of low contaminations.
- The sensitivity can be improved thanks to coincidence measurements.

- Materials selection for rare physics events experiments
- Detection of low level contamination in samples $^{232}\text{Th}$ in Copper, $\text{MoO}_3$ powder

Expecting high sensitivity

RARE DECAYS SEARCHES
$^{180m}\text{Ta}$ rare beta decay

Resonant 0$\nu$ Double Electron Capture ($^{156}\text{Dy}$)

GEANT simulation
An extremely sensitive alpha counter (gas ionization chamber) is purchased from XIA and installed at Y2L in May 2015.

- Background rate: ~ 0.0001 alphas/cm²/hour.
- Essential to study Pb-210 surface contamination for rare process experiments.
TlI powder measurement

- TlI (and NaI) powders measurements
- Pb-210 contamination in powder estimated before crystal growth

**Alpha energy spectrum**

- TlI powder (all events)
  \[ \varepsilon = (5.2 \pm 0.5) \times 10^{-4} \text{counts/cm}^2/\text{hr (250h)} \]

- Po-210 (10µm Mylar)

**Pulse shape discrimination**

- The Po-210 activity is estimated to be
  \[ 1.1 \times 10^{-4} \text{counts/cm}^2/\text{h} \]  
  (< 4 mBq/kg)
At low energies below 20 keV, Pb-210 is the main background source. Where the contamination is (bulk or surface) is also important.
Surface vs Bulk

- Surface component from bulk component can be separated by using a maximum likelihood fit
- Can pinpoint where the contamination happens

Lead Bar Dimension: 10cm x 5cm x 0.5cm
A similar emissivity between two samples.

**NaI(Tl) crystal full peak shifted towards lower energy →**

Deeper surface penetration of Po-210 in the crystal
Max. depth of Po-210 alpha for copper is around 13 µm.

A linear decrease in Po-210 population with surface depth is assumed.
The best fit thickness of the bulk component shows the Po-210 diffusion depth is shallow (0.1 µm) for this sample.
Po-210 depth is estimated at around $1.2+/\text{-}1.0 \, \mu\text{m}$ (stat. only) in the NaI(Tl) crystal. More accurate estimation requires to understand how particle diffusion happens in the surface.
Radon contamination date can be pinpointed with alpha data. Chemical surface cleaning shows removal of contamination.
Ultra-sensitive Radon detector

- Volume = 70 L
- High Voltage = $-1,000$ V
- Bias = 30 V
- Stainless steel with electro-polished inside surfaces
- Shaping amplifier with $\times 12$ gain
- 12 bit 25 MS/s FADC

- Hamamatsu silicon PIN photodiode (S3204-9) $18 \times 18$ mm$^2$

- Hamamatsu charge sensitive amplifier (H4083)
- HV divider circuit
Pulse height distribution

- Pulse height distribution using data of 90 days. No humidity control.
- Crystal ball function is used for all peaks.
- (Sigma) Resolution is less than or equal to 1% for each peaks.

The chart shows the pulse height distribution for different isotopes of polonium (Po210, Po212, Po214, Po218) with their respective number of entries and height in ADC units. The mean, sigma, and resolution values are provided for each isotope.
Stability check

- Profiles of Po$^{214}$ & Po$^{218}$ (selected within 2 sigma) with time
- Linear function fit (ax + b)

\[
\text{Po}^{218} \\
\begin{align*}
\text{a: } & \phantom{0}0.049 \pm 0.034 \\
\text{b: } & \phantom{0}835.963 \pm 0.331 \\
\end{align*}
\]

\[
\text{Po}^{214} \\
\begin{align*}
\text{a: } & \phantom{0}0.101 \pm 0.028 \\
\text{b: } & \phantom{0}1069.612 \pm 0.272 \\
\end{align*}
\]

Test setup is stable
Half lifetime measurements

- Measured the half lifetime of Rn$^{222}$ using Po$^{214}$ & Po$^{218}$ events (within 2 sigma).
- Fitting function: $ae^{-bt} + c$

$T_{1/2}$ (NNDC): 3.8235 days

The background level obtained from the offset is $\sim \frac{1}{2000} \times \text{Max}$

Radon concentration of the initial air (RAD7): 150 Bq/m$^3 \Rightarrow 0.075$ Bq/m$^3$ BKG level
A comparison with RAD7 data

June 5 – 16, 2017 runs
no humidity control, 2hr runs, 2 hr circulation

A full system with dew point meter, filter, flow meter, barometer, etc.. is being prepared.
ICP-MS (Agilent 7900)

- Agilent 7900 is operating since Oct. 2015.
- In a cleanroom nominally designed as class 1000 with >150 air changes/hour.
- A Millipore DI system, in-house acid distillation with a 3 linear meters of chemical hood space.
- Dissolve sample in liquid form, uptake in argon (Ar) gas stream, ionize gas, extract into mass spectrometer, measure trace contaminants.
- Confirmation of purification methods by measuring isotopic or chemical tracers.
- Confidence in systematics at ultra-trace levels is not easily achievable through outsourced measurements.
**Crystals for AMoRE-II**

- \text{dep}^{48}\text{Ca}^{100}\text{MoO}_4 \text{ crystals:} \ \text{dep}^{48}\text{CaCO}_3 \ & \ 100\text{MoO}_3 \ \text{powders}
- \text{Li}_2\text{MoO}_4 \text{ crystals:} \ \text{Li}_2\text{CO}_3 \ & \ 100\text{MoO}_3 \ \text{powders}
- \text{Na}_2\text{Mo}_2\text{O}_7 \text{ crystals:} \ \text{Na}_2\text{CO}_3 \ & \ 100\text{MoO}_3 \ \text{powders}

<table>
<thead>
<tr>
<th>Samples</th>
<th>(232\text{Th})</th>
<th>(238\text{U})</th>
<th>(226\text{Ra (U)})</th>
<th>(224\text{Ra (Th)})</th>
<th>(40\text{K})</th>
</tr>
</thead>
<tbody>
<tr>
<td>(100\text{Mo (99.997%)})</td>
<td>(&lt; 46)</td>
<td>73</td>
<td>8.3</td>
<td>(&lt; 1)</td>
<td>(9)</td>
</tr>
<tr>
<td></td>
<td>(&lt; 61)</td>
<td>149</td>
<td>3.8</td>
<td>(&lt; 0.8)</td>
<td>(36)</td>
</tr>
<tr>
<td>\text{dep}^{48}\text{Ca}</td>
<td>(&lt; 1000)</td>
<td>(&lt; 1000)</td>
<td>51</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td>\text{Li}_2\text{CO}_3 (99.998%)</td>
<td>9.6</td>
<td>414</td>
<td>0.95</td>
<td>0.41</td>
<td>9.0</td>
</tr>
<tr>
<td>\text{Na}_2\text{CO}_3 (99.997%)</td>
<td>(&lt;52)</td>
<td>(&lt;52)</td>
<td>4.15</td>
<td>0.52</td>
<td>31.5</td>
</tr>
</tbody>
</table>

**Requirements for \(238\text{U} \ & \ 232\text{Th}\): ~ \mu\text{Bq/kg in crystals} \rightarrow \sim 1,000 \text{ reduction}**
MoO$_3$ has the transition from the solid to the gas phase around 700 °C. → Some impurities, U/Th, are still in the solid phases.

Decontamination factor (DF) in sublimation

\[
D.F. = \frac{\text{initial impurity}}{\text{final impurity}}
\]

ICP-MS results at 720 °C

<table>
<thead>
<tr>
<th></th>
<th>Sr</th>
<th>Ba</th>
<th>Th</th>
<th>U</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial</td>
<td>6,605</td>
<td>1.37M</td>
<td>224</td>
<td>4,205</td>
</tr>
<tr>
<td>final</td>
<td>&lt;70</td>
<td>0.012M</td>
<td>&lt;100</td>
<td>&lt;90</td>
</tr>
<tr>
<td>D.F.</td>
<td>&gt;94</td>
<td>113</td>
<td>&gt; 2</td>
<td>&gt; 46</td>
</tr>
</tbody>
</table>

Note: Sr, Ba & Ra are the same family in periodic table
Summary

- Two of 100% HPGe detectors are running for measurements of various detector materials (i.e., crystals, copper, powders,..) after improving their shielding.
- A well-type Ge detector is available for measurements of samples obtained in the purification processes of raw materials.
- An array of 14 HPGe detectors is constructed in March 2017 for ultra-low background measurements and rare decay experiments. Background runs are on-going.
- A gas type alpha counter is running actively for measurements of alphas from the surfaces and bulks of detector materials since May 2015.
- A refurbished radon detector with an excellent resolution being prepared for the measurement of the air from the radon reduction system.
- An ICP-MS (Agilent 7900) is running well to test samples of detector materials and purification processes since Oct. 2015.