Gamma-ray Spectroscopy with High Purity Germanium Detectors

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Introduction

The Black Hills Underground Campus (BHUC) is located on the 4850L of the Sanford Underground Research Facility (SURF) in Lead, SD. It currently houses 5 low background counting systems for determining the radiopurity of materials [1].

Materials used in underground physics experiments such as those studying neutrinoless double-beta decay, neutrino oscillations, and dark matter detection require low levels of radiation, high radiopurity. Materials' radioactivity is screened using gamma-ray spectroscopy. In the BHUC, high-purity germanium (HPGe) detectors are used to measure the concentration of radioactive elements such as U, Th, and K present in a sample material [1].

These assays inform various underground physics experiments on the background of materials to be used in dark matter detectors. This is useful in experiment development to determine which materials should be used to maintain low-backgrounds and informs experiments on how background from the materials used in apparatus will influence the data [1].

In the summer of 2025, the BHUC returned from its temporary location in the Davis campus to its permanent location in the Ross campus (see Fig. 1). Each detector had to be deconstructed in the temporary BHUC cleanroom and reconstructed at the permanent BHUC.

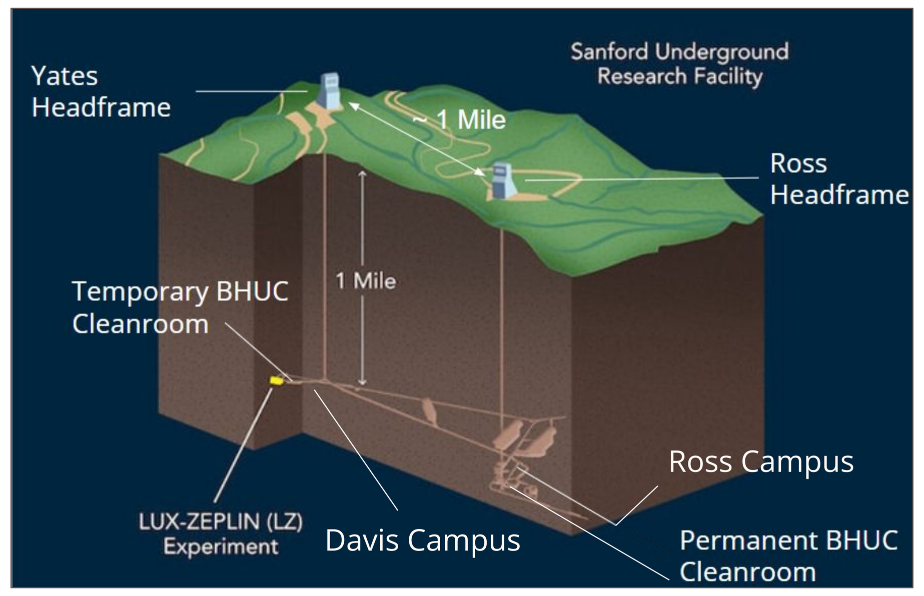

Fig 1. Above-ground and 4850L of the Sanford Underground Research Facility with locations of the temporary and permanent BHUC cleanrooms [2].

Background

The BHUC currently houses 5 HPGe detectors: Morgan, Maeve, Mordred, RHYM/RESN, and the Twins. Gamma-rays are emitted through the decay process of radioactive isotopes in sample materials such as U-238, Th-232, K-40, and their daughter nuclides (see Fig. 2) [3]. The result of the decay process often is an excited daughter nuclide which will give off energy as it returns to its ground state [3]. The amount of energy it was excited by is quantized and is released by means of a photon, a gamma-ray (depending on the energy), which will then interact with the Ge-crystal [3].

Gamma-ray Spectroscopy

- Gamma rays transfer energy to the electrons in Ge atoms in the Ge crystal. Compton scattering, the photoelectric effect, and pair production are the mechanisms in which energy is transferred from the gamma-ray to the Ge crystal (see Fig 3). [3]
- The scattering of electrons within the Ge crystal leads to the creation of electron-hole pairs. These electron-hole pairs are what create measurable signals in the detector. [3]
- The identity of the source radioisotope is determined by the energy of the gamma-ray which corresponds to the energy measured by the detector.

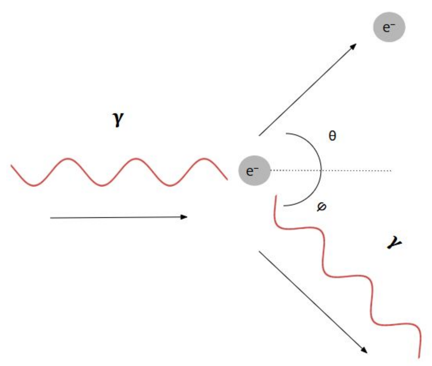

Fig 3. Compton Scattering

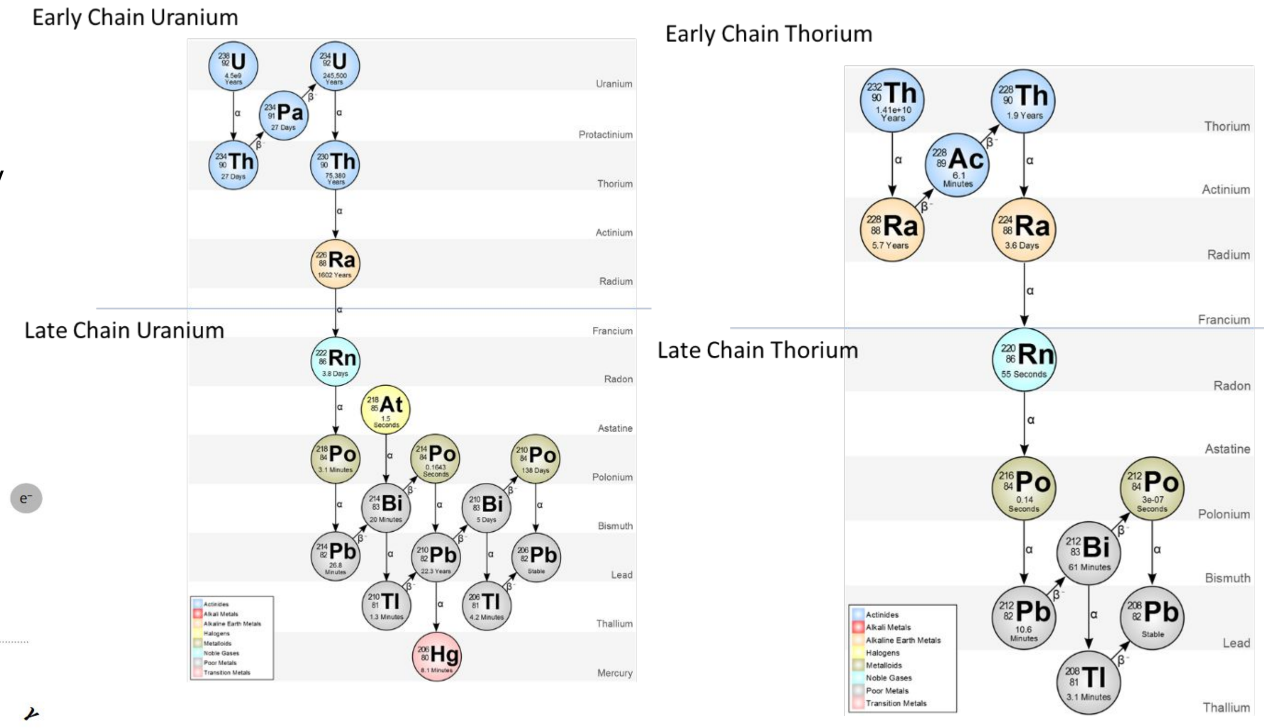

Fig 2. Decay Chain for Uranium (left²) [4] and Thorium (right³) [5].

Methods

Calibration and Measurement

To calibrate the detectors, we use a sample with a known concentration of U, Th, and K, this is known as Table Mountain Latite (TML). The TML is placed into a marinelli beaker or a petri dish which is then placed over the HPGe crystal. [3]

In addition to the TML spectrum, we take a background spectrum as a control to determine how much radiation is present without a sample. Due to the typically low levels of radioactivity present in rare event search samples, spectra are collected for 1-2 weeks [6].

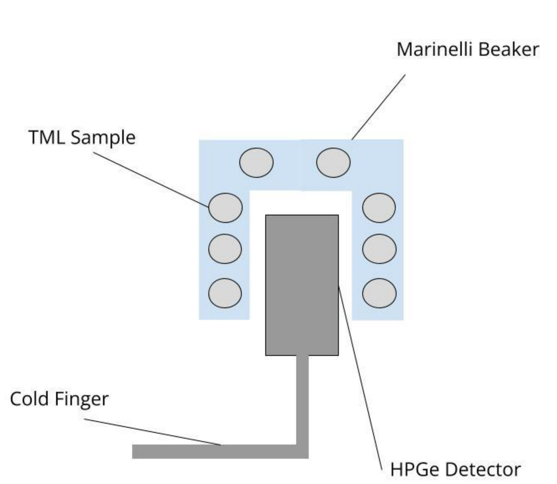

Fig. 4 Sample in Marinelli beaker

$$C = \frac{N_{peak}}{\epsilon_{peak} M_{sample} P_\gamma LT}$$

C - Concentration (ppb)
N - Counts
ϵ - efficiency
M - mass of the sample (g)
P_γ - Probability of Emission
LT - Live time of the sample (Min)

Eqn. 1 - Equation used to determine isotope concentration [3].

Analysis with Software

- Many β-decays in the U-238, Th-232, and K-40 decay chains result in a gamma-ray with a quantized amount of energy being released. The amount of gamma-rays detected are measured in counts [3].
- To determine the concentration of an isotope present in a sample, the counts in a certain energy range must be calculated. This is done by taking the area under the curve of a spectrum. A program called PeakEasy [7] is used to identify lines in a spectrum and determine the total counts associated with each isotope's decay (N_{peak}) in Eqn.1. N_{peak} is then divided by the efficiency, ϵ (see Eqn.2), the mass of the sample, *M*, the probability of a gamma-ray being emitted, P_γ, and the live time of the sample in minutes *LT* [3].
- An efficiency curve can be fit by using spectral lines with known efficiencies to determine the efficiency of another spectral line with an unknown efficiency (Fig.5) [3]. Efficiency is defined by Eqn.2 as being the number of photons of a specific spectral line being detected (*Detected Photons*) divided by the number of photons actually emitted by the decay (*Emitted Photons*) [3].

$$\epsilon = \frac{Detected\ Photons}{Emitted\ Photons}$$

Eqn. 2 - Efficiency Equation, used to determine the unique efficiency for each detector, spectrum, and sample geometry [3].

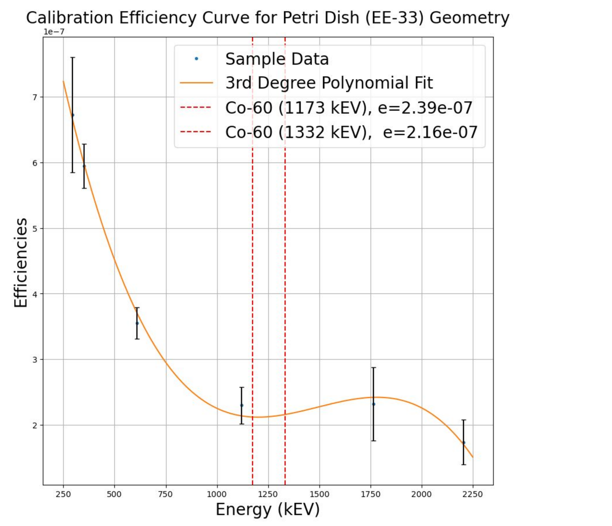

Fig. 5 Efficiency Curve used to determine efficiency of Co-60

Setup of the BHUC

Moving the Detectors

Pb-shields surround the HPGe detectors. Pb is commonly used in experiments to shield from radiation [6]. 2,227 of Pb bricks (~57,000 lbs) were moved for the reconstruction of the detectors. In addition to Pb, the detectors are surrounded by Mylar to prevent Rn from the environment seeping into the detector and to keep N_2 gas inside the detector, purging it of unwanted contaminants [1].

Components of the Detector

1. Pb-shield - Blocks radiation from outside the sample-chamber.
2. Copper (OFHC) - Used to absorb fluorescent x-rays from the Pb-shield. [3]
3. Mylar - Covers any air gaps in the Pb-Shield, helping to keep Rn out and N_2 inside of the detector.
4. Carriage - Filled with Pb, covers opening to the sample chamber. Is pulled out to access the crystal when loading a sample.
5. LN2 Dewar - Used for cooling the Ge-crystal to prevent thermal noise in the detector [Gilmore/BHUC].

Clean Room Protocols

6. The BHUC is a class-1000 cleanroom [1].
7. Nearly every material that was moved had to be wiped with Isopropyl Alcohol Wipes (IPA wipes) to maintain cleanliness of clean room. Apparatus being moved underground were wrapped in plastic wrap before movement to maintain cleanliness.

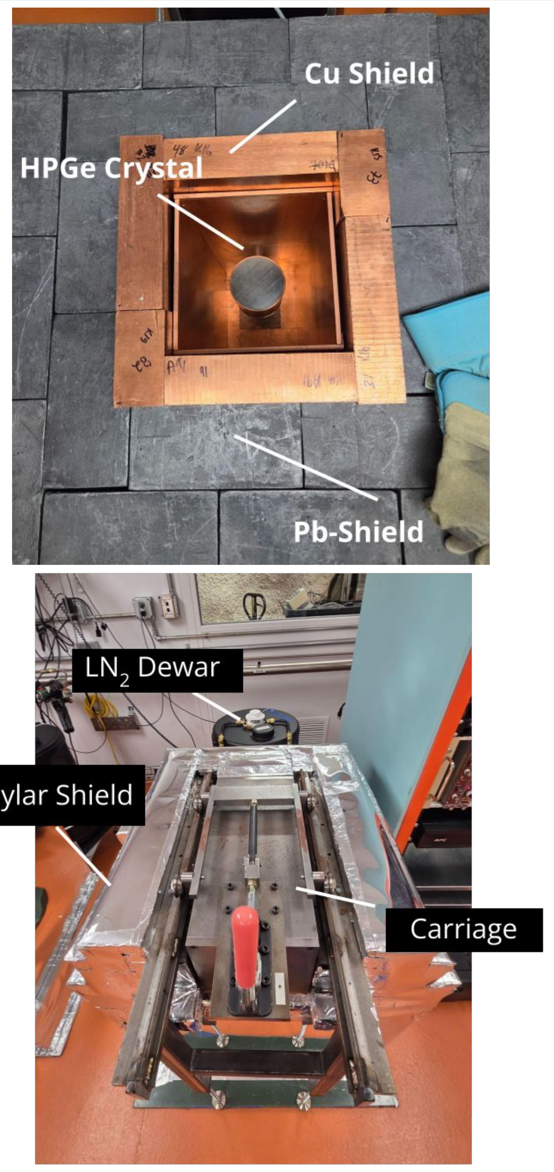

Fig 6. (Top) Constructing Mordred Detector. (Bottom) Finished Morgan Detector

Data

- The analyzed sample is 316L stainless steel powder which is used for laser metal printing (see Fig. 7). Materials such as these could have many applications to designing underground physics experiments.
- From the collected spectra, net counts (sample - background) are determined for each spectral line (see Fig. 8). Eqn. 1 is then used to determine the concentration of U, Th, and K present in the sample (see Table 1 for the concentrations present in the Zurich powder spectrum).

Table 1. Concentrations of Isotopes in the Zurich powder sample.

	Concentration (mBq/Kg)
U (Early)	≤ 6.0
U (Late)	14.3 ± 1.1
Th (Early)	≤ 1.7
Th (Late)	≤ 1.0
K-40	≤ 3.9
Cs-137	≤ 2.09
Co-60	≤ 0.90

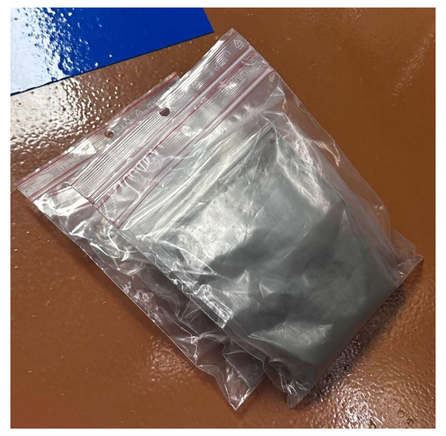

Fig. 7 Picture of Zurich powder sample

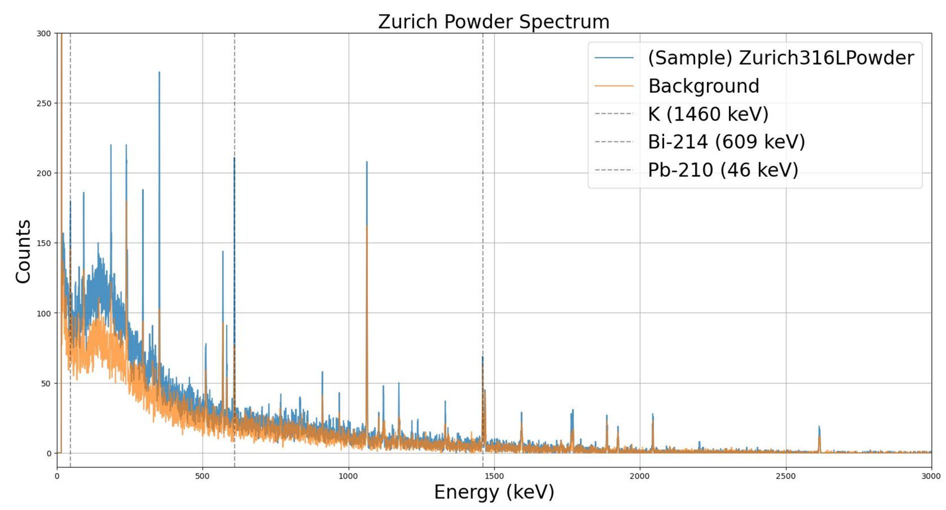

Fig. 8 Spectra of both the Zurich powder sample and background.

Conclusion & Future Work

The BHUC HPGe detectors have successfully been moved back to the Ross Campus. Background data is currently being recorded to allow a comparison of the backgrounds for each of the detectors in the current BHUC to when the detectors were in the Davis Campus. This will help identify if there are any environmental conditions that need to be considered for the continued use of the detectors in the BHUC. Software will be developed to streamline the process of determining the concentration of elements in the sample after we have determined the counts of each element in the spectrum. The BHUC will shortly resume routine sample analysis.

Acknowledgements

This project was funded by NSF Award 2150517. We thank the National Science Foundation for funding research experiences for undergraduate students such as this project. We also thank Olivia Cantrell, Dylan Chase, Isabella Lopez, Zachary Spangler, and Doug Tiedt for their help moving the HPGe detectors and the Pb-shielding. We would also like to thank Jay Hockhalter and Robyn Varland for ensuring we had the proper PPE underground and giving us rides between the Yates and Ross shafts.

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