Maximizing the KURF Materials Screening Sensitivity with Cosmic Ray Veto

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(Dated: July 24, 2019)

Secondary muons are high-energy particles created from the interaction of cosmic rays with atoms in Earth's atmosphere. They are a major source of high-energy background interference for Virginia Tech's high-purity germanium (HPGe) detector housed at the Kimballton Underground Research Facility (KURF) in Ripplemead, VA. Though muon interference is partially shielded by the rock overburden at KURF, our team works to integrate the HPGe detector with a two-layer muon detector to veto persistent radiation caused by muon events. After fitting the muon detector to the physical specifications of the lab site, we used the HPGe present in-house at Virginia Tech and a sodium iodide scintillator to progressively modify the detector readout system, including applying remote controls, using a logic gate redundancy to increase efficiency, and selecting an increased photoelectron threshold for the muon detector to remove low-energy interference. Before installation at KURF, we found muon-energy peaks in spectra from samples containing known sources to have decreased to less than one count per day above 4 MeV, the range where our data is taken. Ongoing features of this research include analyzing data taken on location at KURF to further improve the integration and subsequently using the integrated detectors to observe radioisotopic sample backgrounds in high-purity environments.

I. INTRODUCTION

Used to analyze the physics of radiation, including questions on dark matter, neutrinos, and double-beta decay, gamma-ray spectroscopy presents unique challenges in the wide range of energies to resolve and the large background that exists due to the radioactive isotopes within all matter. Thus, decreasing background radiation is a significant preoccupation of high-energy physicists. In the ultrahigh energy range (typically above about 14 MeV), cosmic ray muons form a significant portion of that radiation. Formed from the decay of cosmic pi mesons which are themselves formed from the decays of primary cosmic ray particles colliding with particles in Earth's atmosphere, cosmic ray muons travel close to light speed and many reach the earth despite their short lifetimes of only 2 μs[1].

In the past, our group at Virginia Tech has used lead and cement shielding around our detectors to block lower-energy background. We have also installed radiation detectors at the KURF in Giles County, Virginia, a limestone mine operated by Lhoist of North America. The site features low levels of natural radiation in addition to strong muon shielding: Virginia Tech operates a lab near the entrance of the mine which sees a rock overburden of 300 meters water-equivalent (m.w.e.), in addition to formerly housing a detector deeper in the mine which saw a rock overburden of 1450 m.w.e. This reduces the flux from 170 Hz/m^2 unobstructed to 0.6 Hz/m^2 within the mine[2].

In the following paper, we describe the process of integrating the radiation detector, a high-purity germanium (HPGe) detector, with a muon detector in order to veto background data caused by remaining muon interference, as well as detailing the schema of the detectors themselves.

II. GERMANIUM DETECTOR

A. Geometry

The HPGe detector used at KURF was manufactured by ORTEC as part of their GEM series of coaxial HPGe detectors. The central piece of the detector is a crystal made of π-type HPGe[3] and formed in a closed-ended bulleted coaxial shape, wherein a hollow cylinder of the crystal is closed on one side and rounded at its edges. This geometry maximizes the active volume of the detector's depleted region, up to 750 cm^3[4], while maintaining low capacitance within the detector. The lithium-diffused n$^+$-type contact is on the outer surface of the crystal and is 700 microns thick while the ion-implanted p$^+$-type contact is on its inner surface and is 0.3 microns thick.

The crystal is placed on an aluminum mount inside an aluminum vacuum capsule along with the front end of the preamplifier to minimize unwanted decay events. The preamplifier discriminates photoelectrons formed in the HPGe crystal to compose the spectrum and transmits to the back end of the preamplifier, contained not in the vacuum but within an electronic shroud inside the detector. Beside it inside the shroud but outside the vacuum seal is the high voltage filter, which will trigger a failsafe on the preamplifier module if the temperature falls out of range. The high-voltage module is used to reverse-bias the crystal depleted region, thus increasing the voltage through which charged particles travel and thereby increasing resolution accuracy. The cooling rod adjacent to the detector's electronic shroud leads via plastic tubing to the nitrogen dewar, in thermal contact with it at all times.

B. Readout and Analysis

The preamplifier, which takes in Nuclear Instrumentation Module (NIM) logic, outputs a transistor-transistor logic (TTL) signal to the EASY-MCA-8K multi-channel analyzer by ORTEC, which in turn reads out the voltage pulses via USB to the MAESTRO software installed on a PC. The MAESTRO software then resolves the spectra into histograms where counts are plotted against analog-to-digital converter (ADC) channel. The energy of a photoemission within the detector and the ADC channel voltage measured from it are proportionate, making scaling in a HPGe detector reliably linear. Thus, it can be calibrated using any source with known decay lines, typically ^{60}Co or ^{137}Cs. Spectra can also be analyzed using the ROOT tools developed by CERN for C++, using a series of algorithms written by members of our group. The resolution of the HPGe is particularly fine as compared to other high-energy radiation detectors, resolving with FWHM in the hundreds of eV from energies above 90 keV.

C. Operation

The HPGe detector at KURF is housed in the Model HPLBS-2 low-background lead shield manufactured by Putnam Technology, Inc. From the outside in, the shield is composed of 0.375 in (0.95 cm) of low-carbon steel outer casing, 4 in (10.16 cm) of lead, 0.3 in (0.76 cm) of tin, and 0.64 (1.63 cm) of copper. The lead shield deflects gamma and x-ray interference, while the tin and copper deflect bremsstrahlung, photons created by Compton scattering, and neutron radiation which escapes the lead shield. The shield was sterilized before installation at KURF and both the shield and detector are kept in a clean room under a vinyl curtain, the air circulated constantly to minimize radon deposition. The detector is also protected by a vinyl sleeve which is only removed when the sample is being replaced. To refresh the internal environment, the detector capsule can also be flushed with nitrogen from the adjacent dewar, also manufactured by Putnam Technology. While data is being collected, the detector is maintained at 77 K to reduce the generation of leakage current. For this reason, the HPGe crystal is kept in constant thermal contact with the liquid nitrogen dewar. The dewar holds 20 gallons, or about eight days' worth of liquid nitrogen when the detector is operating.

III. MUON DETECTOR

A. Geometry

The muon detector is modeled after a prototype of the double chooz experiment at Nevis Laboratory [2]. It consists of 96 plastic scintillator bars with 60cm x 5cm x 1cm dimensions covered in a reflective coating made of TiO_2 to enhance luminosity. When ionizing radiation interacts with matter it will excite a large number of molecules. When these excited molecules return to their ground state will give rise to the emission of photons resulting in radiolumiescence, also know as scintillation [5]. The scintillator bars are divided into four modules of 24 bars each with 12 on top and bottom. A wavelength shifting (WLS) fiber is inserted into each scintillator bar to guide the light to the one of the four Hamamatsu H8804 multi-anode photo multiplier tubes (PMTs). Photomultipliers use an electron multiplier system allowing detection of single photons [6]. The PMT boards are daisy chained to one another using Ethernet Cat6 cables, connected to a readout USB board.

The four modules that make up the detector are placed in perpendicular alignment atop one another, so that the 1st and 3rd module are at the same orientation, as are the 2nd and 4th. The top and bottom layer of each module are offset by 2.5 cm. This displacement assists in the eight geometrically overlapping hits that we are looking for from the muons, distinguishing themselves from other particles. This design significantly reduces background events from radioactivity, gamma rays, or other instrumental noise such as electronic or optical crosstalk. Gamma rays between 0.5 and 10 MeV do pass through the detector and can have the potential to create a false muon hit. However, in order to make it through more than one layer, the gamma ray need to participate in Compton scattering two times. There is a 30-40% chance that Compton scattering will take place one time but only a 2-5% chance of it taking place twice. Furthermore, when eight geometric hits are required this chance of a false hit from a gamma ray goes to zero. This particular assembly was chosen to maximize muon detection efficiency and to minimize background from random coincidences in the detector such as dark current or natural radioactivity. It has been previously shown that the probability of those events creating eight overlapping hits in the detector is negligible [2].

B. Efficiency

The 2.5 cm offset results in small portions of the detector that are unable to detect muons meaning some muons will do activate the WLS fibers. In addition, this offset leaves overhang of scintillation bars that is 2.5 cm on each side, resulting in a the edges of the detector unable to track muons and decreased efficiency [7].

The efficiency can be set in both the hardware and software. We calculated the PE threshold value that correlated with maximum efficiency to be at 2 PE. This value is implemented at KURF for data collection and veto. Collecting data at a threshold that is too high has the potential to bias our data to incoming muons at a very small zenith angle. An incoming muon at a large angle will deposit very high energy on one bar but the perpendicular bar will get almost none, meaning that muon's energy will be below the threshold cut applied. The threshold can also be adjusted on the software level when analyzing the data. The only constraint here is that the cut must be made at an equal or greater amount to the PE value set in the hardware for data acquisition.

C. Electronics

Our system is comprised of five electronic modules. The quad linear fan in fan out system takes the initial input from the four PMTs. The 3 fold logic unit controls the channels and gate setting, allowing us to couple channels for the veto and adjust the efficiency through choice of AND or OR logic functions. The dual timer discriminates between input signal based on the width of the signal received[8]. The 2 Chooz clock module puts out a 62.5MHz pulse signal that increments an internal counter to help us track the timing of the hits[7]. Next, the four channel NIM desktop programmable HV power supply powers the four PMT boards. The quad scaler and preset counter allows us to empirically calculate the efficiency of each board. There are also two circuit boards used. The clock signals of each PMT board are connected to the low voltage board. The other circuit board is used as a readout device connected to the 2 Chooz clock signal, the transmitting and receiving ends of the CAT6 cables, the clock cable that comes from the low voltage power supply, and a USB that connects to the computer performing data acquisition.

D. Crosstalk

We are concerned with both optical and electronic crosstalk. Optical crosstalk takes place on the face of the PMT. The PMTs are arranged with at least a 2 mm distance between every fiber so there are no neighboring fibers. This choice minimizes but does not eradicate the optical cross-talk between the pixels. As light is passed from the WLS fiber to the PMT, the light will be slightly over distributed due to the extremely close proximity of the pixels. Some of the light that goes into the neighboring pixel will create optical crosstalk. Electrical crosstalk can take place in the dynode chain and in the readout board. As the dynode chain multiplies the electrons, it is possible for an electron to mistakenly travel into a different dynode chain. It then starts to multiply in that dynode chain, creating a small signal in a pixel next to it that is not receiving data [8].

E. Veto

The goal of the muon veto is to tag muons with high efficiency and provide tracking information for muons that pass through the HPGe and muon detectors [8]. Since it is not possible to shield this HPGe detector from muons while it studies radiation, the muon detector provides us with the ability to accurately classify muons that pass through the HPGe detector and veto these false hits from the radiation data collected. The veto happens in real time, as the muons pass through the detectors. The muon detector works more quickly than the HPGe detector so we have taken advantage of the dead time of our cables and adjusted the dual timer module to properly align the hits on the detectors. This results in about 200 ns of dead time for the muon detector. The veto allows us to further minimize the cosmic ray background detected by the HPGe detector without affecting the collection time of the HPGe detector. Serving this purpose, the muon veto is an essential part of working to more accurately measure the radiopurity of the materials being tested by the HPGe detector at KURF.

F. Data Analysis

First, an autoprocess script is run to convert the files received from the detector into ROOT [9] nTuples that can be read and used by the analysis software. Once converted, the files we want to analyze are put into a group that tells the software their file size and run time. The analysis script called mega microsoft is used to perform the rest of the analysis. The output of the analysis includes: the number of entries, calculation of the offsets between the PMTs, calculation of bilayer hits, bilayer hits on each PMT, fourfold calculation, eightfold calculation, bilayer and overall efficiencies, and comparison of the hit rate with and without efficiency corrections made. We are also provided with a reconstruction of the data. Once the analysis has been completed we also have the option to run a script that compares our data to a Monte Carlo simulation of muon flux. This comparison is helpful for us to better understand our collected data compared to what is predicted.

IV. RESULTS

The muon detector was originally built to work on its own to measure muon flux rates at Virginia Tech. By converting the device to a more portable sub detector

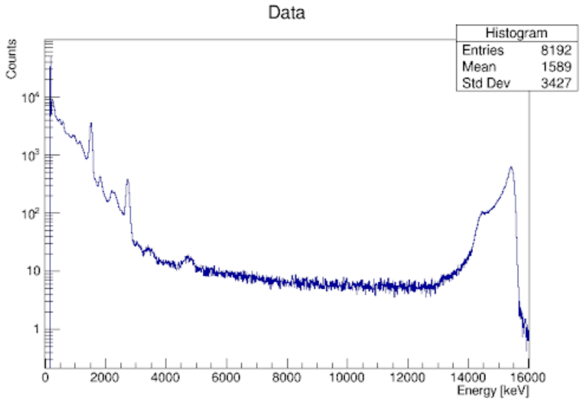


FIG. 1: Frequency of measurements corresponding to energy values during a background taken on an NaI(Tl) scintillator, with no veto.

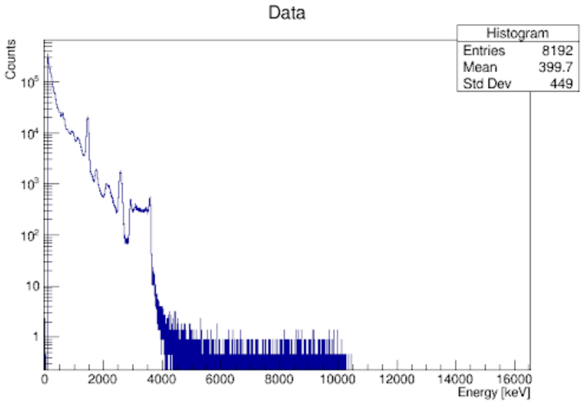


FIG. 2: Frequency of measurements corresponding to energy values during a background taken on an NaI(Tl) scintillator, where data is taken anti-coincidental to muon veto.

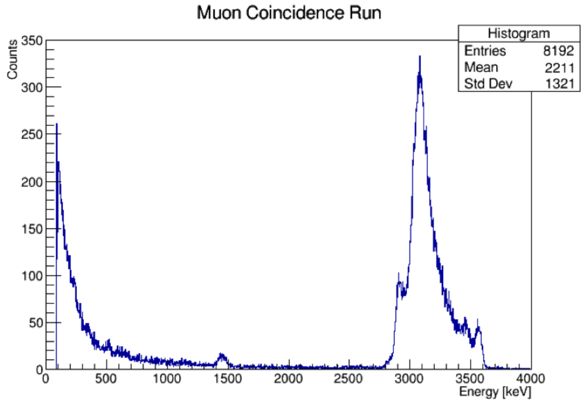


FIG. 3: Frequency of measurements corresponding to energy values during a background taken on an NaI(Tl) scintillator, where data is taken coincidental to muon veto.

to be coupled with a HPGe detector, the purpose has changed. The detector now works as a muon veto for the HPGe detector. It has been important for us to run tests to ensure that the veto works properly. This test was performed at Virginia Tech by coupling the muon detector to a NaI(Tl) scintillator detector that is being studied in our lab. Previous background spectra taken using this NaI(Tl) detector resulted in a spectra which showed unidentified energy deposited between 14 and 16 MeV. This peak was hypothesized to be caused by muons. Our group set the NaI(Tl) scintillator in anti-coincidence with the muon detector for 18 hours and vetoed 30 μs of data for each muon interaction in the detector. Our prediction was that this unidentified peak would not be present in the anti-coincidence data.

We observe in the final spectrum that contributions above 4 MeV have been reduced to less than 1 count per day or completely erased, confirming our assumption that the highest-energy depositions were caused by muons. The intermediate energies between 4 MeV and the highest-energy contributions were inferred to be the Compton continuum of the muon decay. This confirmed our expectation that the muon detector would be successful as a subdetector to veto muon hits on the HPGe at KURF.

However, higher-energy contributions than the Tl-208 line at 2615 keV still remain in the data. During a subsequent run taken in coincidence, muon energies were not deposited in the detector but the region between 2.6 and 4 MeV was easily observable, along with a small fraction of the generally-present background. We expect that the muons' energy may not be measured because of the relative locations of the muon detector and the NaI(Tl) detector; the NaI(Tl) was located above the muon detector, so while the veto applied early enough to prevent the data being recorded during the anti-coincidence, it opened late enough during the coincidence sampling that the muon had already passed through.

The data below is taken from a series of background tests performed at Virginia Tech in the lower-elevation lab, where overburden is 170 Hz/m^2. Placement of measured muons corresponds well with simulated data. Azimuthal angular measurements are well within error bounds in each case. Zenith angle of the incoming muons skews toward smaller angles, but not to the extent that had been predicted. We expect that this was caused by the building shadow: because the detector was within on the lowest level of a multistory building that the upper levels acted as a sh to muons and decreased the vertical flux. At KURF, this effect may appear differently, since the rock surrounding the detector is not equally deep in all directions.

We can see from the angular distribution on the x and y axes that our data is not significantly biased by the chosen hardware threshold of 2 PE. The spike in counts at zero represent muons entering the muon detector at the vertical. It can be seen from the two plots that the

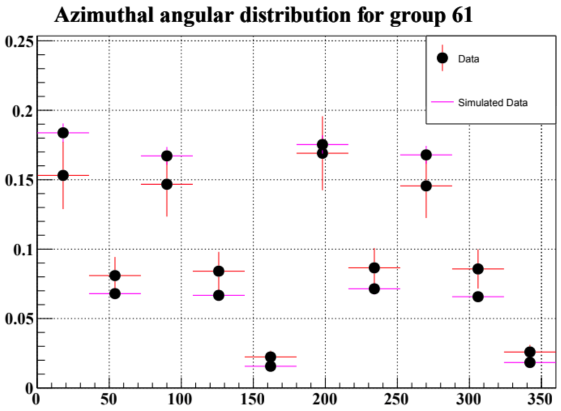


FIG. 4: Azimuthal angular distribution for incoming muons through detector.

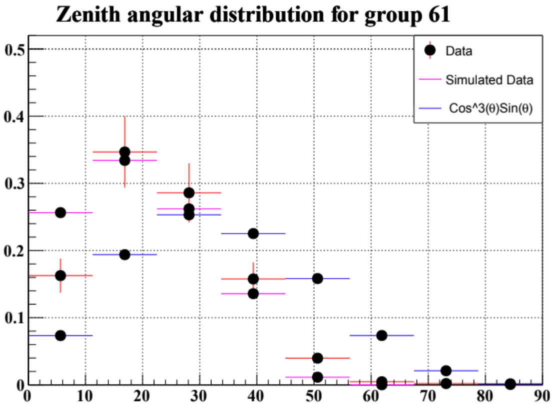
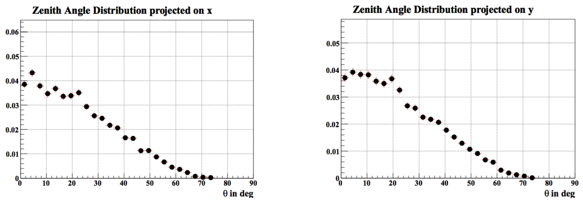


FIG. 5: Zenith angular distribution for incoming muons through detector.

muon counts are inversely proportional to the theta angle. This finding supports the claim that our detector's muon detecting efficiency is highest for incoming muons at the vertical and drops as the incoming muons begin to make contact closer to the horizontal.



(a) X-projection

(b) Y-projection

FIG. 6: Zenith angular distribution for incoming muons through detector, projected onto x- and y-axes

V. CONCLUSION

Underground physics is extremely beneficial for shielding detectors from unwanted particle hits and other causes of background noise on detectors. By coupling the HPGe detector with the muon detector, the radiopurity of samples will further increase, allowing for more accurate data and results from tests performed at KURF. In the future, we anticipate using the coupled detectors to further investigate the disparity between data vetoed in the anti-coincidence veto and data caught during the coincidence veto. We will also continue monitoring the performance of the veto at KURF as compared to at Virginia Tech's home labs. Alternative logic choices between channels have been proposed which may lead to higher yield; with their installation, we hope to see a stronger veto and overall more effective data.

VI. ACKNOWLEDGEMENTS

We would like to thank Lhoist North America Limestone Mine for allowing us to conduct research at the Kimballton Underground Research Facility. This project could not have been successful without the wonderful assistance from the Virginia Tech Physics Department's machine shop and Thomas O'Donnell's lab group, specifically from Andy Jackson and Kevin Marquez Diaz. Thank you to Betty Wilkins for her advice and support throughout the project, as well as the Center for Neutrino Physics for hosting us. The work of Jessica Christian and Stephanie Toole was supported by the National Science Foundation REU grant number 1757087.

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