A NEW GAMMA-GAMMA COINCIDENCE ANALYSIS SYSTEM

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Sponsored by the National Nuclear Security Administration

Award No. DE-AC05-RL01830/PL10-CASCADES-NDD05

ABSTRACT

The Pacific Northwest National Laboratory is currently developing a custom software suite capable of automating many of the tasks required to accurately analyze coincident signals within detector arrays. This capability is required to enable rapid analysis of data collected with a new low-background intrinsic germanium (HPGe) array at PNNL. The system is designed to intelligently identify which algorithm best applies to a dataset in order to quantify the activities of isotopes observed in the sample. The HPGe array is designed for high detection efficiency, ultra-low-background performance, and sensitive γ-γ coincidence detection. Traditional methods for constructing ultra-low-background detectors were followed, including use of materials known to be low in radioactive contaminants, use of ultra pure reagents, and clean room assembly. The cryostat is constructed mainly from copper electroformed into near-final geometry at Pacific Northwest National Laboratory. The array was recently installed into a new shallow underground laboratory facility with approximately 35 meters water equivalent overburden. Details of the new facility, the CASCADES detector assembly, initial background results, and the status of the analysis development are presented.

OBJECTIVES

A current research effort at Pacific Northwest National Laboratory (PNNL) is focused on building two germanium arrays in ultra-low-background cryostats, and the development of a multi-coincidence data analysis package to demonstrate robust fission product measurements utilizing these arrays. The design and performance expectations for the instrument have been discussed previously (Keillor et al, 2009). Each cryostat houses seven high-purity germanium crystals (HPGe); these cryostats are built using a limited set of materials known to have very low levels of radioactive impurities. The vast majority of each cryostat is made from pure copper (< 1 μBq/kg) electroformed into near-final geometry at PNNL under class 1000 clean room conditions.

The instrument is designed to take advantage of low background performance, high detection efficiency, and γ–γ coincidence signatures to provide unprecedented gamma spectroscopy sensitivity. This effort is focused on improving gamma analysis capabilities for nuclear detonation detection applications, e.g., nuclear treaty monitoring. The instrument also has the potential to contribute to basic nuclear physics research. For example, the potential for this detector to measure the half-life of predicted rare decay modes of ^{130}Te is being investigated (see Mizouni et al., 2011).

This paper briefly reviews the cryostat design and construction; it then provides details of the current system shielding, initial performance of the active anti-cosmic shield, and initial backgrounds and spectroscopic performance of the array. Spectral analysis products generated by the analysis package in development are also presented.

RESEARCH ACCOMPLISHED

Cryostat and HPGe Array Assembly

Assembly of an ultra-low-background cryostat housing a seven-crystal HPGe array was reported previously (Keillor, et al., 2010), and is summarized here. The first cryostat was initially assembled with all components except the IR shield and HPGe crystals/mounts. This includes installation of the low-background front-end electronics package (LFEP), wiring, and preamplifiers. The cryostat vacuum and thermal performance were tested prior to installation of the 7 HPGe crystals.

Cooling for the cryostat is provided by a liquid nitrogen (LN) Dewar custom-built by Technifab corporation, with a 100 L capacity. Initial tests of this Dewar indicate that it uses about 1 kg of LN per day with no external load. LN use with the cryostat attached is about 4 L/day, or 3.25 kg/day. Thus the Dewar itself consumes about 2.3 W, while the cryostat represents a thermal load slightly above 5 W. This thermal load is consistent with our expectations. In the completed system, both cryostats will be cooled by the same Dewar; total LN use should be on the order of 7 L/day after installation of the 2nd cryostat.

Seven P-type coaxial HPGe crystals, nominally 63 mm diameter by 70 mm height, were installed into the cryostat in mid-May 2010. This was completed in a clean room with the cryostat disconnected from the Dewar. The installation of each crystal assembly was relatively simple; signal wire was attached to the center connection of the crystal, then the high-voltage (HV) wire was fed through the appropriate hole in the cold plate and attached. Following this, the crystal holder was placed on the cold plate and secured with electroformed copper nuts on the three posts. Once a crystal was secured, the cryostat was inverted to allow crimping of the signal wire to a lead attached to the gate of the LFEP. This sequence was repeated until all 7 crystals were installed. Crystal installation was accomplished in a single session in the clean room, in less than 4 hr. Figure 1shows a sequence of photos taken during the installation.

Shielding

The system was recently moved from a surface-level laboratory to a new shallow underground facility at PNNL with an overburden of ~35 m water equivalent (m.w.e.). Minor modifications to the shield design were accomplished as a part of the move, reducing much of the lead thickness from ~41 cm (16 in.) to ~25 cm (10 inches). Passive shielding consists of ~25 cm (10 in) of lead, a layer of cadmium foil external to the lead, and ~15 cm (6 in.) of borated polyethylene (a mixture of 5% and 30% sheets that were available). An enclosure surrounds the passive shield for radon exclusion, but this portion of the system is not yet complete around the shield door. Finally, ~5 cm (2 in.)

thick BC-408 plastic scintillator paddles surround the passive shield. The shield system, with shield door open, is shown in Figure 2.

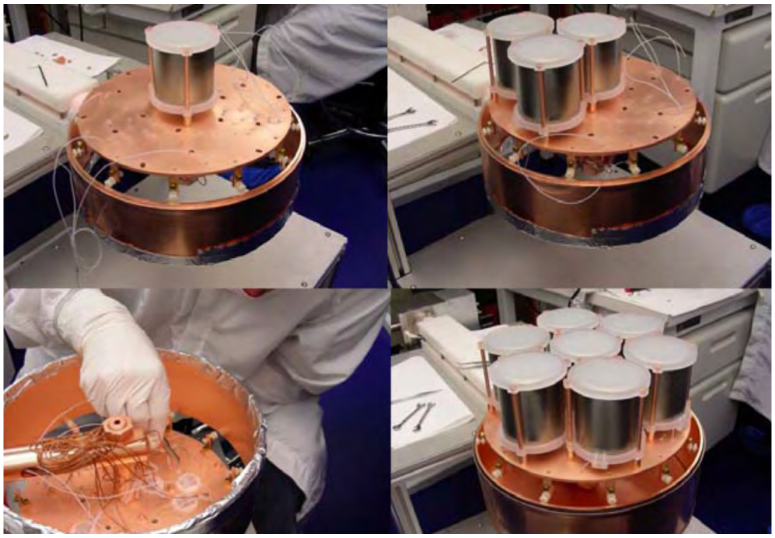

Figure 1. This sequence of photos shows progress of installation of the HPGe crystals. The frame in the lower left shows the cryostat inverted to allow easier access for crimping the signal wire.

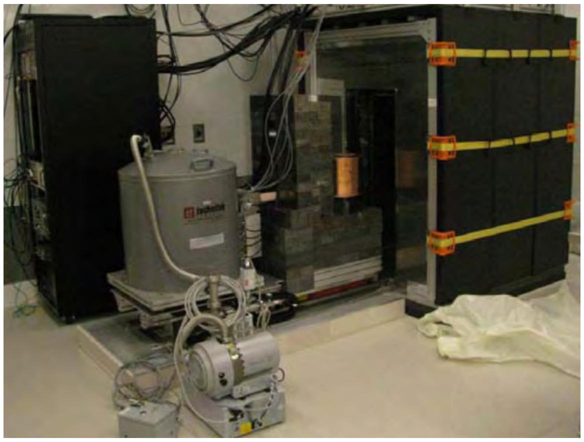

Figure 2. First 7 crystal array installed in the new shallow underground laboratory at PNNL.

The active cosmic veto shield is comprised of 15 BC-408 plastic scintillator panels installed on five surfaces of the passive lead shield. Panels will be added to the door side to finish the active shield after completion of the radon exclusion enclosure. The goal of this veto system is to detect and exclude cosmic-ray generated interactions within the germanium array. Each plastic panel has a size of roughly 17.5 in × 2 in × 70 in and makes use of a single photomultiplier tube to detect the scintillation light (widths and heights vary slightly to accommodate the shield dimensions). On each side protected by the active veto, the signals from three panels are combined ("t'd" together); the direct PMT signal is subsequently read out by an XIA PIXIE-4 waveform digitizer.

The active shield is currently being operated with a ±1 µs anti-coincidence window; cuts are applied during post-processing of the data and it is possible to modify this anti-coincidence window at a later date. Background rejection efficiency is measured at 73%; however, we know that a significant portion of the current background is associated with radon daughter isotopes and ^{210}Pb associated bremsstrahlung (see below). Suppression of the 511 keV annihilation peak is 94.2%, and we take this as a better estimate of the efficiency of the active shield to tag cosmic-ray-related background events. This rejection efficiency will improve with addition of the final panels around the shield door, and may also be improved by further optimization of the anti-coincidence time window.

Initial Background and Spectroscopic Performance

The preliminary underground background rate is ~5800 counts per day (cpd) per crystal in the range of 40–2700 keV. This rate was determined from a 4.7 day measurement with 5 crystals of the array operating. The background measurement is dominated by a significant continuum extending out to ~700 keV, peaks associated with the decay of radon daughter isotopes, and the 511 keV annihilation peak. To verify that the continuum was internal to the shield (rather than cosmic-ray associated), we placed a 2.5 cm (1 in.) thick copper plate approximately 2 cm above the cryostat entrance window. This configuration reduced the rate to ~5000 cpd/crystal with an obvious reduction of the continuum (see Figure 3). We currently attribute the continuum to ^{210}Pb-associated bremsstrahlung. The passive shield was designed with sufficient space to add ~5 cm of copper as an inner lining; we will pursue this strategy to mitigate the background contribution of ^{210}Pb bremsstrahlung. Our target background for this system, at this depth, is < 1000 cpd/crystal.

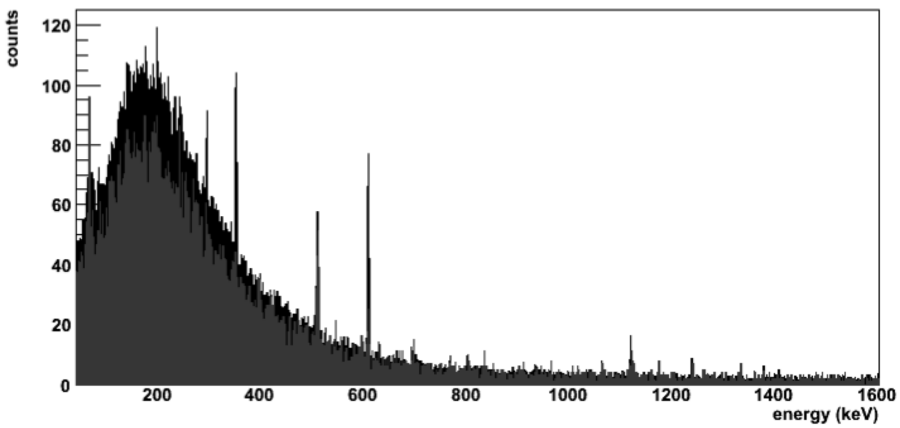

Figure 3. A comparison of background spectra from the first HPGe array is shown. The black region indicates the typical background in the system, while the gray region shows the effects of additional bremsstrahlung shielding (a 1 in. copper plate) placed over the sample window.

We collected the first spectroscopic data with the array on June 22, 2010. The first results were very encouraging, with all seven channels active. Early testing showed five crystals operating with energy resolution in the range of 2.2–2.4 keV at 1332 keV, while one crystal could not be fully biased due to apparent high leakage current, and one crystal suffered from poor energy resolution due to high frequency noise on the baseline. A summed spectrum including the five well-performing crystals was created with a 2.3 keV energy resolution at 1332 keV. In conjunction with the move underground, we performed a bake-and-pump cycle that improved the leakage performance of the crystal with high leakage current. However, the overall noise performance in the new laboratory is poorer than that achieved prior to the move; we are currently troubleshooting the source of noise.

Data Acquisition

The signal processing path consists of PNNL LFEP sockets mounted near each crystal, on the opposite side of the cold plate, through Belden 8700 micro-coaxial cable (with the external jacket stripped to reduce background contribution) to a 50-pin vacuum feedthrough. Seven PGT RG-11 preamplifiers are mounted on a housing covering the outside of the vacuum feedthrough. Preamplifier power is supplied from Ortec 4003 preamplifier power supplies (NIM). Preamplifier signals are processed with a PXI crate holding five XIA PIXIE-4 digitizers. Software control of the DAQ hardware uses an in-house PNNL data acquisition program called NYX [Cooper, et al, 2010]. NYX provides much the same functionality as the Windows-based software supplied by XIA, however is based in Linux to provide a higher degree of stability. This acquisition system allows the user to specify different levels of data collection, with three key modes being (1) basic MCA-style spectra for each crystal, (2) time and energy list mode data, and (3) digitized waveform data for each observed pulse. The system also records coincident hit pattern information for modes two and three.

Development of Analysis Framework

The CASCADES detector array uses a new software analysis package developed by PNNL as part of the project's efforts. This tool set, known as *melusine*, is intended to provide off-line data handling and analysis tools needed for multiple crystal arrays that are not handled by commercial analysis software. While it directly addresses the calculations used in the CASCADES project, it is designed to be easily adapted to other applications that include complicated coincidence detection schemes. Though incomplete, today *melusine* is successfully used for most off-line analysis being done on this research project. This includes construction of a wide variety of histograms (with and without cuts on the data), energy calibrations, as well as peak search and fitting. Also, many additional features are presently under development to meet present and future needs.

The *melusine* package is built upon ANSI C++ and makes use of the ROOT data analysis framework [http://root.cern.ch/drupal/] that offers a free, but highly capable, collection of data visualization, manipulation, and management tools. The result is a light-weight system that is supported across all major development platforms. Today, the *melusine* package is operating on a number of Windows, Mac, Linux, and Unix systems with minimal effort to move among the platforms.

Data acquisition and processing for this project is a multi-step process. Figure 4shows a flowchart of how data is currently processed within the system. PIXIE-4 waveform digitizers produce binary data that is received by the PNNL data acquisition software NYX and stored on disk. At this point the *melusine* preprocessor is used to convert the PIXIE-4 data into a device-independent format that is also easy to process by ROOT-based tools. Next, the *melusine* analysis routines are used to produce histograms and analysis.

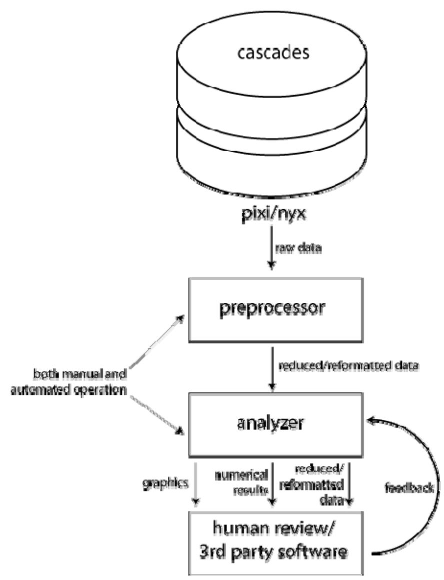

Figure 4. Data pathway for CASCADES using the *melusine* preprocessor and analyzer programs.

The *melusine* tools for CASCADES are designed to be flexible in how they are used. In the first step, the preprocessor converts the PIXIE-4 data into a simple ROOT tree. In this form, the user has easy access to the data by using a ROOT interactive session to examine data integrity and can produce simple histograms with minimal effort. The *melusine* analysis program requires event data to be presented in this simple but well-defined ROOT tree form to decouple the event data from the hardware that produced it. By separating the data formatting from the analysis tools in this manner, the *melusine* system can easily handle data produced by other sources. For example, simulated data can be produced in a manner that it can be processed identically to experimental data collected by the HPGe array. Alternatively, data from a different detector array, perhaps not even based on the PIXIE-4/NYX data acquisition system, could be easily reformatted for analysis using *melusine*.

For processing beyond that supported natively by ROOT sessions, a configuration file is created by the user to define which histograms and analyses are desired. Options such as coincidence requirements, cuts, fits, calibrations, and others are defined in this configuration file and users have the choice of directly editing configuration files or using a graphical user interface (GUI) to set these values. The actual generation of histograms and other analysis can be accomplished by command-line calls (which are suitable for automation) or interactive GUI sessions.

Today the *melusine* tools offer the ability for users to produce histograms based on a wide range of cuts and coincidence requirements. Users can restrict spectra based on channel, multiplicity, energy range, veto status, graphical cuts, and others in ways that significantly extend the analysis framework in ROOT. In fact, the system presently can easily produce many more spectra than is practical for human consumption within the timeframes expected where answers such as isotope identification and activity will be most useful. For this reason, one of the objectives for the system is the intelligent evaluation of all supported techniques on a case-by-case basis. Where possible, the focus is on automation to relieve the processing burden from the researcher. Early progress along these lines includes assisted-energy calibration processes (see Figure 5).

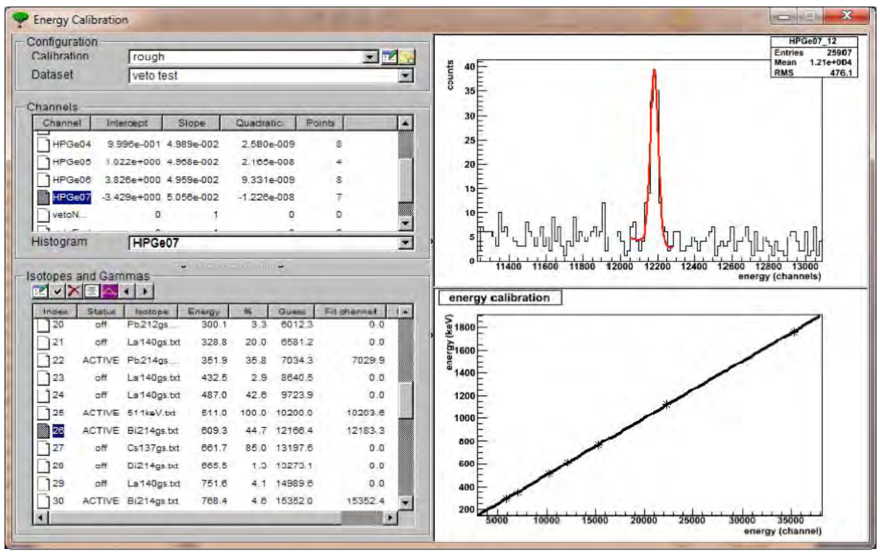

Figure 5. Screen capture of the *melusine* analyzer assisting during an energy calibration.

Reducing the amount of manual processing is especially critical when it comes to coincidence analysis. Many calculations in the coincidence plane require numerous regions of interest for each energy studied and the computer is better suited to the repetitive and calculation-intense tasks involved. The issue is not simply one of identifying peaks but also in calculating the optimal analysis technique to be used. Attributes such as detection efficiency, peak-to-total ratios, and signal-to-strength measurements have to be considered in each case to get optimal performance. While *melusine* is useful today for many analysis tasks, many of these features are in the planning or early development stages.

CONCLUSIONS AND RECOMMENDATIONS

A seven-HPGe crystal array has been successfully assembled in a cryostat designed and constructed using ultra-low-background materials and techniques. Initial background performance, as well as the effectiveness of the active anti-cosmic veto, is being determined now that the system has moved to a new shallow underground laboratory at PNNL. Additional background reductions are anticipated, and will be realized with completion of the radon suppression system, active anti-cosmic shield, and addition of a copper lining inside the passive shield. All copper parts for the 2nd cryostat have been completed, and assembly is in progress.

Collecting initial data has provided us with valuable measurement data sets to process through the *melusine* data analysis package currently under development. This effort is early in its development, however can already provide significant capabilities for reconstructing data acquired with the array in multiple ways. Current efforts are focused on efficiency calibration routines and activity calculations. The long-term vision is that the system will be capable of performing multiple parallel analyses to establish the most sensitive data reconstruction for a measurement on an isotope-by-isotope basis.

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