Characterization study of a broad-energy germanium detector at CJPL (Postprint)

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Abstract

The ability of background discrimination using pulse shape discrimination (PSD) in broad-energy germanium (BEGe) detectors makes them as competitive candidates for neutrinoless double beta decay (0{ }eta̲eta̲) experiments. The measurements of key parameters for detector modeling in a commercial p-type BEGe detector are presented in this paper. Point-like sources were used to investigate the energy resolution and linearity of the detector. A cylindrical volume source was used for the efficiency calibration. With an assembled device for source positioning, a collimated 133Ba point-like source was used to scan the detector and investigate the active volume. A point-like source of 241Am was used to measure the dead layer thicknesses, which are approximately 0.17 mm on the front and 1.18 mm on the side. The described characterization method will play an important role in the 0{ }eta̲eta̲ experiments with BEGe detectors at China JinPing underground Laboratory (CJPL) in the future.

Full Text

Characterization Study of a Broad-Energy Germanium Detector at CJPL

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Abstract

The ability of broad-energy germanium (BEGe) detectors to discriminate backgrounds using pulse shape discrimination (PSD) makes them competitive candidates for neutrinoless double beta decay (0   ) experiments. This paper presents measurements of key parameters for detector modeling in a commercial p-type BEGe detector. Point-like sources were used to investigate the energy resolution and linearity of the detector, while a cylindrical volume source was employed for efficiency calibration. Using an assembled device for source positioning, a collimated ^{133}Ba point-like source scanned the detector to investigate the active volume. A $^{2\ 1}$Am point-like source measured the dead layer thicknesses, which are approximately 0.17 mm on the front and 1.18 mm on the side. The described characterization method will play an important role in future 0   experiments with BEGe detectors at the China JinPing underground Laboratory (CJPL).

Key words: BEGe, characterization, dead layer, 0   , CJPL

1. Introduction

Broad-energy germanium (BEGe) detectors are competitive candidates for neutrinoless double beta decay (0   ) experiments using germanium detectors. Benefiting from a unique electrode structure with a rather small inner electrode for signal output, BEGe detectors achieve better energy resolution and stronger pulse shape discrimination (PSD) power for single-site events (SSEs) and multi-site events (MSEs) compared to semi-coaxial germanium detectors [1,2]. This PSD capability plays a crucial role in background discrimination for 0   experiments. GERDA employed several BEGe detectors for 0   detection in Phase I and achieved the most sensitive result among all similar experiments using germanium detectors [3]. In the ongoing Phase II, GERDA is utilizing many more BEGe detectors to fully capitalize on their excellent performance [4].

Research into the PSD power of BEGe detectors requires establishing fine detector models for both Monte Carlo (MC) simulation and pulse shape simulation (PSS) to evaluate the discrimination efficiency of developed PSD methods and study features of pulse shapes induced by different physical events. In such models, the active volume size and dead layer thickness are key parameters for obtaining accurate simulation results, making it necessary to extract specific values through characterization of BEGe detectors. GERDA has devoted considerable effort to characterizing BEGe detectors [5-7], while other researchers have also conducted studies [8,9]. These previous works consistently addressed gamma spectrometry performance, extraction of key detector parameters, and investigation of pulse shape features.

Future 0   experiments with BEGe detectors will be conducted at the China JinPing underground Laboratory (CJPL). As the world’ s deepest underground laboratory, CJPL has a rock overburden of 2400 m (approximately 6720 m w.e.) [10] and a muon flux of 2.0×10&’ m&*s&, [11]. As a preliminary study of BEGe detectors for 0   experiments at CJPL, this work presents the characterization of a commercial BEGe detector at CJPL. The energy resolution and linearity were investigated, efficiencies were calibrated, the active volume was scanned with a collimated ^{133}Ba point-like source, and the dead layer thicknesses on the front and side were measured with a $^{2\ 1}$Am point-like source.

2.1. Detector Specification

The detector under investigation is a commercial p-type BEGe detector (Model BE6530) produced by Canberra [12], which has been stored at CJPL for approximately 4 years. A schematic view of the detector configuration is shown in [Figure 1: see original paper]. The germanium crystal has a diameter of 91.1 mm and a height of 31.4 mm. The small boron-implanted p electrode is 13.5 mm in diameter and serves as the signal contact. The lithium-diffused n electrode covers most of the remaining crystal surface, serves as the high-voltage contact, and is separated from the p electrode by an annular groove. The crystal is held by a copper cup in a 1.6-mm-thick aluminum endcap and placed 8 mm from the front window. The front window consists of 0.6-mm-thick carbon composite to enhance detection efficiencies for low-energy gamma rays penetrating from the front. The recommended bias voltage is +4500 V.

The data acquisition system comprises a charge-sensitive pre-amplifier (Model 2002C), an integrated digital signal analyzer (Model DSA-LX), and Genie-2000 software. The pre-amplifier is integrated with the detector and pre-amplifies the charge signal from the p electrode. The digital signal analyzer (DSA) integrates the functions of the high-voltage module, main amplifier module, and multi-channel analyzer module of an analog electronics chain. The DSA records signal pulse shapes from the pre-amplifier with a fast sampling ADC (FADC), extracts their energy information through firmware using the trapezoidal shaping algorithm, and finally sends the information to the Genie-2000 software, which handles production and storage of energy spectra.

2.2. Experimental Procedure

The measurement procedures for energy resolution, linearity, efficiencies, active volume size, and dead layer thicknesses are described in detail below. For energy resolution measurements, point-like sources of $^{2\ 1}$Am, ^{133}Ba, $^{13\ }$Cs, Co, and $^{1\ 2}$Eu were positioned approximately 7 cm above the detector’ s top surface. These point-like sources contain radioactive materials sealed as a dot (1 mm in diameter) in a thin plastic film (Φ 32 mm × 4 mm). Initially, the Co source was measured alone to adjust the parameters (rise time and flat top) of the DSA’ s trapezoidal shaping algorithm. Subsequently, energy resolutions for additional gamma peaks with energies between 59.5 keV and 1408 keV from the various radioisotopes were obtained to study their dependence on gamma peak energy.

For linearity measurements, the same sources were used and the peak positions of corresponding gamma rays were recorded to verify the linearity of the detector’ s response to gamma ray energy deposition. Efficiency calibration employed a certified cylindrical volume source obtained from the UK’ s National Physical Laboratory (NPL) in a comparison measurement. This source, made of filter medium, contained more than 10 radioactive isotopes (${}^{2\ 1}$Am, Co, Co, Y, Mn, etc.) and was placed on the detector’ s top surface to obtain the dependence of absolute detection efficiency on gamma ray energy. For each gamma ray of interest, the net peak count was calculated and used to deduce the corresponding detection efficiency, accounting for measurement time, gamma ray emission intensity, and source radioactivity.

Active volume size was investigated by scanning the same ^{133}Ba source used for resolution measurements, but collimated with a 1-cm-thick stainless-steel collimator. The source scanned the BEGe detector along the diameter of the top surface and the height of the lateral surface in steps of 1 cm or 0.5 cm. The collimator was positioned as close as possible to the endcap surface to prevent overlap of illuminated crystal areas in adjacent steps. Incident collimated gamma beams were perpendicular to detector surfaces, with constant measurement time for each position during a given scan. The net peak count of the 81 keV gamma ray was continuously recorded, and the active volume size was deduced from its variation.

Dead layer thickness measurements utilized the same ${}^{2\ 1}$Am source. In each measurement, the source was placed at a fixed position and the full-energy-peak (FEP) detection efficiency for the 59.5 keV gamma ray was obtained experimentally (given the certified source activity of ~8290 Bq). Simultaneously, the FEP detection efficiency was obtained through MC simulation based on GEANT4 with an identical experimental setup. The simulation was repeated while varying the corresponding dead layer thickness value in the detector model, yielding the dependence of FEP detection efficiency on dead layer thickness. This relationship was fitted with an exponential function [13], and the actual dead layer thickness was determined by interpolating the fitted function to the experimentally measured FEP detection efficiency.

2.3. Assembled Collimation Device

To position point-like sources at various locations around the detector, an assembled stainless steel device was constructed to facilitate characterization. [Figure 2: see original paper] shows a concept view of this manually operated device, which consists of three main components: (a) a holding structure—an L-shaped holder that supports all other parts and maintains stability; (b) a position-fixing part—through rotation of the central shaft and movement of the source holder, point-like sources can be positioned above the top surface or around the lateral surface with 1 mm precision; and (c) removable collimators—with these collimators, the detector can be scanned with collimated radiation beams in different directions. Components (a) and (b) can be disassembled into smaller parts for convenient transportation and storage.

3.1. Energy Resolution

For germanium detectors, energy resolution typically refers to the full width at half maximum (FWHM) of a gamma peak. With a smaller inner signal contact, BEGe detectors can achieve lower electronic noise levels and consequently better energy resolution than semi-coaxial HPGe detectors [14]. In 0 experiments, good energy resolution is crucial for narrowing the region of interest, distinguishing signals from background, and improving experimental sensitivity [15].

[Figure 3: see original paper] presents variations in energy resolution for gamma rays from Co (1173 keV & 1332 keV) when adjusting the rise time and flat top of the DSA' s trapezoidal shaping algorithm. In Figure 3: see original paper, the FWHM fluctuated slightly within 0.05 keV while the rise time was fixed at 6 µs and the flat top varied between 0.8 µs and 1.2 µs. In Figure 3: see original paper, with the flat top fixed at 1 µs, the FWHM increased rapidly when the rise time fell below 2 µs but fluctuated slightly within 0.06 keV between 2 µs and 10 µs. For subsequent measurements, the flat top and rise time were fixed at 1 µs and 6 µs, respectively. Based on further measurements with the point-like sources described in Section 2.2, the FWHM was obtained and fitted as a function of gamma peak energy (in keV) by [16]:

$$FWHM = a \times E + b,$$

where E is the gamma peak energy and a, b are coefficients. The result is shown in [Figure 4: see original paper]. The FWHM of the 1.33 MeV peak is approximately 1.66 keV (~0.125%), which is outstanding among germanium detectors.

3.2. Linearity

Germanium detectors exhibit excellent linearity in response to different energy depositions, reflected by the goodness-of-fit when the energy calibration curve is fitted to a linear function. Good linearity enables clear discrimination of different physical events based on their energy information. To study the energy response linearity of the BEGe detector, the point-like sources described in Section 2.2 were measured. Since the highest-energy gamma ray is the 1408 keV line from $^{1\ 2}$Eu, the summation peak resulting from coincidence of the two Co gamma rays was also included to compensate for possible deviations from linearity in the high-energy region during fitting. The detector demonstrates notably good linearity, as shown in [Figure 5: see original paper] where energy is in keV.

3.3. Efficiency

Absolute detection efficiencies of the BEGe detector were measured using the certified cylindrical volume source described in Section 2.2, with involved gamma rays listed in . [Figure 6: see original paper] shows the efficiency curve as a function of gamma ray energy (in keV), fitted by [17]:

$$\ln eff = a + b \times \ln E + c \times (\ln E) * + d \times (\ln E) F,$$

where eff is the absolute detection efficiency, E is the gamma ray energy, and a, b, c, d are coefficients. The curve reaches its maximum at approximately 70 keV and decreases almost linearly above 200 keV in double logarithmic coordinates. Before the maximum, gamma rays penetrate the entrance window and n electrode with increasing probability as their energy increases; once they reach the detector’ s active volume, nearly all are absorbed. After the maximum, gamma rays are absorbed with decreasing probability as their energy increases.

3.4. Volume Scanning

As described in Section 2.2, measurements were conducted with the collimated ^{133}Ba source, focusing on variations in the net peak count of the 81 keV gamma ray, shown in [Figure 7: see original paper]. Figure 7: see original paper presents results along the top surface diameter, where position 0 cm corresponds to the surface center. Ideally, the curve should exhibit a flat central plateau with a sharp decline at the germanium crystal boundary. However, the net peak count was maximal at the center, slowly decreasing as the source moved outward and rapidly declining at the boundary. This difference is attributed to incomplete collimation from the 1-cm-thick collimator, chosen as a compromise due to the source’ s notably low activity (several kBq level). With a thicker collimator, collimation improved but the peak nearly disappeared into background. This incomplete collimation significantly impacts result accuracy. Defining the active volume diameter as the width where net peak count exceeds 50% of the central value yields an active volume of approximately 87.7 ± 2 mm, compared to the manufacturer’ s crystal diameter of 91.1 mm.

Figure 7: see original paper shows results vertically along the lateral surface, where position 0 cm corresponds to the same horizontal level as the crystal center. The curve does not behave as expected due to incomplete collimation and the crystal’ s surrounding configuration. To understand the result and determine the internal structure of the Al endcap, an X-ray image was generated, shown in [Figure 8: see original paper]. When the source moved along the crystal’ s upper part, net peak counts decreased due to shielding by the thicker copper holder; when the source moved near the upper boundary, net peak counts increased abnormally rather than decreasing, because uncollimated gamma rays had increasing detection probability through the large top surface. Conversely, net peak counts increased when the source moved along the lower crystal part with its thinner copper holder, then continued decreasing at the boundary due to shielding by the copper holder covering the bottom surface. Consequently, determining active volume thickness from these results is difficult, and a well-collimated, strong source will be necessary for future improvements.

3.5. Dead Layer

Germanium detectors always have dead layers on surfaces where electric fields are too weak for complete charge collection [17]. If a radioactive particle deposits energy in these dead layers, the recorded energy deviates from the actual deposition. For commercial BEGe detectors, manufacturer-provided dead layer thicknesses are merely reference values, and dead layers may grow over time [18], particularly when detectors are stored without high voltage for extended periods. The certified $^{2\ 1}$Am point-like source described in Section 2.2 was used for dead layer thickness measurements.

For front dead layer measurement, the $^{2\ 1}$Am source was positioned approximately 4 cm above the detector’ s top surface center, producing the energy spectrum in [Figure 9: see original paper]. The 59.5 keV peak was fitted using a combination of Gaussian and linear functions, from which net peak count and FEP detection efficiency were derived. The curve in [Figure 10: see original paper] from simulation shows FEP detection efficiency dependence on front dead layer thickness, with straight lines indicating the determined thickness value. The final result is 0.166 ± 0.011 (stat) ± 0.1 (syst) mm, compared to the manufacturer’ s typical value of 0.3 µm. The standard systematic errors for all dead-layer thickness results in Section 3.5 were conservatively estimated as 0.1 mm, covering errors from source positioning, fitting, simulation, and other processes.

For side dead layer thickness measurement, the $^{2\ 1}$Am source was placed at two different rotation angles (0° and 45° directions) on the same horizontal level as the germanium crystal center, approximately 3 cm from the lateral surface. Similar analyses as for the top measurement were performed. The energy spectrum and FEP detection efficiency dependence on side dead layer thickness for the 0° direction are presented in [Figure 11: see original paper] and [Figure 12: see original paper], respectively, while 45° direction results are omitted. The determined thickness values for both directions are listed in , which agree well and yield an average of 1.179 mm compared to the manufacturer’ s typical value of 0.5 mm.

The ^{133}Ba point-like source was also used to measure side dead layer thickness at two rotation angles as a benchmark against the $^{2\ 1}$Am measurements. The ^{133}Ba source was positioned at the same locations as the $^{2\ 1}$Am source. The process was similar except that the ratio between FEP detection efficiencies of two ^{133}Ba gamma rays was obtained in both experiment and simulation. The FEP detection efficiency ratio between a lower-energy and higher-energy gamma ray is sensitive to dead layer thickness, enabling thickness determination. Here, FEP detection efficiency ratios of the 81 keV gamma ray to the 276 keV, 303 keV, 356 keV, and 384 keV gamma rays were calculated. The energy spectrum and FEP detection efficiency ratio dependence on side dead layer thickness for the 0° direction are presented in [Figure 13: see original paper] and [Figure 14: see original paper], respectively, while 45° direction results are omitted. The determined thickness values from different gamma ray pairs are also listed in , all consistent with ^{2} ^{1}Am source results.

4. Summary

Characterization of a commercial BEGe detector using an assembled collimation device was conducted at CJPL as preliminary study for future 0 experiments. The detector's gamma spectrometry performance is excellent: the 1.33 MeV peak energy resolution reaches 1.66 keV, energy response linearity is perfect, and the efficiency curve behaves as expected. Scanning yielded an active volume diameter of approximately 87.7 mm, though a reliable thickness measurement was not obtained due to imperfect experimental conditions. Front and side dead layer thicknesses are approximately 0.17 mm and 1.18 mm, respectively, having increased compared to manufacturer typical values. The determined dead layer thickness values will be applied to detector models for MC simulation and PSS, while active volume size will be remeasured using a strong, well-collimated source.

Future work includes pulse shape studies of the BEGe detector. A systematic pulse shape analysis method will be established for BEGe detectors, contributing to background discrimination in prospective 0 experiments at CJPL.

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Note: Figure translations are in progress. See original paper for figures.