Background Suppression Using Pulse Shape Analysis with a BEGe Detector for Neutrinoless Double Beta Decay Search with GERDA

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Abstract. A pulse shape analysis for distinguishing between double beta decay-like interactions and multiple-scattered photons was performed for the first time using a BEGe-type detector. This discrimination method is included in the research and development for the second phase of the GERDA experiment, since active background suppression techniques are necessary to reach sensitivity for the ^{76}Ge neutrinoless double beta decay half life of > 10^{26} years. A suppression of backgrounds in the energy region of interest around the ^{76}Ge $Q_{\beta\beta}$ = 2039 keV is demonstrated, with $(0.93 \pm 0.08)\%$ survival probability for events from ^{60}Co, $(21 \pm 3)\%$ for ^{226}Ra, and $(40 \pm 2)\%$ for ^{228}Th. This performance is achieved with $(89 \pm 1)\%$ acceptance of ^{228}Th double escape events, which are analogous to double beta decay.

Keywords: Ge detectors; Pulse shape analysis; Background suppression; Double beta decay.
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INTRODUCTION

The GERDA experiment [1], currently under construction at the Laboratori Nazionali del Gran Sasso in Italy, will search for neutrinoless double beta decay ($0\nu\beta\beta$) of ^{76}Ge. Germanium detectors, enriched in ^{76}Ge, will be operated bare in high-purity liquid argon, which will serve simultaneously as a coolant for the germanium detectors and as a shield against external radiation. GERDA sensitivity to $0\nu\beta\beta$ half-life is expected to reach $\sim 2 \cdot 10^{26}$ years after about 100 kg·y of ^{76}Ge exposure. Novel active background suppression techniques are necessary to reach the required background level of < 10^{-3} counts/(keV·kg·y) in the region around $Q_{\beta\beta}$ = 2039 keV (a factor of ~100 below the best current values).

$\beta\beta$-decays result in highly localised energy deposition of the two emitted beta particles, while most backgrounds emit γ-radiation. At energies around $Q_{\beta\beta}$, γ-rays have typically mean free paths of several centimetres in germanium, thus deposit energy at multiple dislocated interaction sites. Distinguishing multi-site events (MSE) from single-site events (SSE) is therefore a powerful tool to suppress background. One of the main methods to discriminate MSE from SSE in germanium detectors is the analysis of signal pulse shape [2]. Recently, a p-type detector with a miniaturized readout electrode has been developed [3], which exhibits superior pulse shape discrimination performance compared to usually used coaxial detectors. This result triggered our study of commercially available Broad Energy Germanium (BEGe) detectors [4], which have a qualitatively similar electrode configuration.

The Experimental Setup

The detector (a *p*-type HPGe) is a modified Canberra model BE5030 with dimensions of ∅8 cm × 3 cm and a mass of ~880 g. The detector housing has a standard-thickness aluminium window and front Ge dead layer as opposed to the thin-window low-absorption configuration which is normal for BEGe detectors. The front-end electronics and data acquisition system (DAQ) consists of a Canberra 2002CSL preamplifier, with a specified noise of 570 eV and a rise time of 20 ns; a non-shaping amplifier built in-house; and a Struck SIS 3301 14-bit, 100 MHz flash-ADC. Besides recording signal traces, the flash-ADC DAQ software uses real-time Gaussian filtering to shape signals and produce energy spectra. The detector operating voltage was 3.8 kV, and energy resolution was 0.49 keV and 1.63 keV (FWHM) at 59.5 keV and 1332.5 keV, respectively. A comprehensive study [5] has shown flawless charge collection performance and stability of the detector.

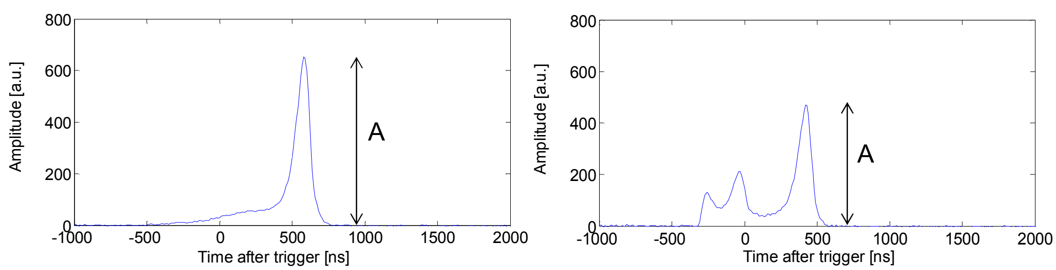

FIGURE 1. Candidate SSE (left) and MSE (right) current signals reproduced offline by 10 ns differentiation and 50 ns smoothing from recorded voltage signals, with an approximately equal energy. The maximal current amplitude *A* is proportional to the highest energy deposition within an event.

Pulse Shape Discrimination

The MSE/SSE discrimination is based on a single parameter: the ratio *A/E* of the maximal current signal amplitude *A* (Figure 1) to the event energy *E* (proportional to the integral of the current signal). The pulse-shape cut is calibrated with a ^{228}Th source. The 1592.5 keV double-escape peak (DEP) from the 2614.5 keV emission line of ^{208}Tl (a ^{228}Th progeny) was used as a SSE-rich substitute for ββ-decay events. The distribution of the *A/E* ratio from ^{228}Th events can be seen in Figure 2. The pulse-shape discrimination (PSD) procedure is described in detail and validated in [5].

The background suppression power was tested on data recorded from ^{228}Th, ^{226}Ra and ^{60}Co sources. The acceptance of DEP events was (89.2 ± 0.9)%, and the survival probability of full-absorption γ-ray peaks was on average (10.0 ± 0.2)%. The ^{60}Co events in $Q_{\beta\beta}$ region (created by γ-ray cascade summation events) have a survival probability of only (0.93 ± 0.08)%. ^{226}Ra and ^{228}Th survival fractions around $Q_{\beta\beta}$ were (20.6 ± 3.4)% and (40.2 ± 1.6)%, respectively. Example cut-outs of ^{228}Th and ^{60}Co spectra before and after the PSD cut are shown in Figure 3. Figure 4 gives the survival fractions of different spectral lines, and of ^{228}Th, ^{226}Ra and ^{60}Co events at $Q_{\beta\beta}$.

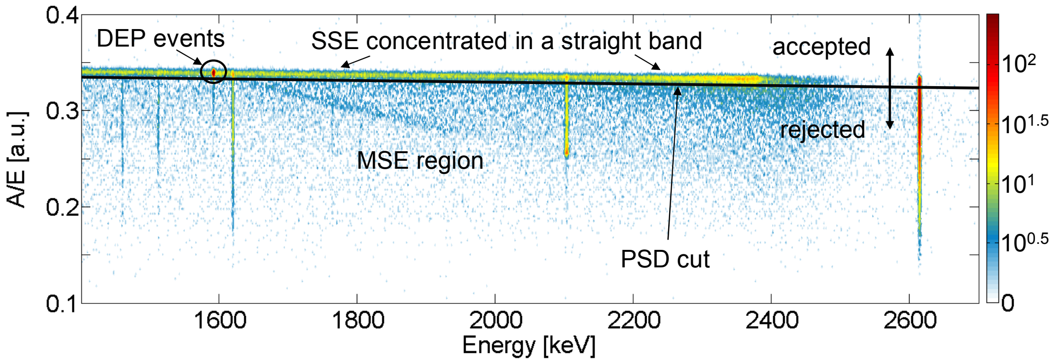

FIGURE 2. Density plot of the *A/E* parameter distribution (in arbitrary units, *a.u.*) in a ^{228}Th spectrum. The scale bar on the right indicates the number of events in a square of 1 keV × 0.0025 a.u.

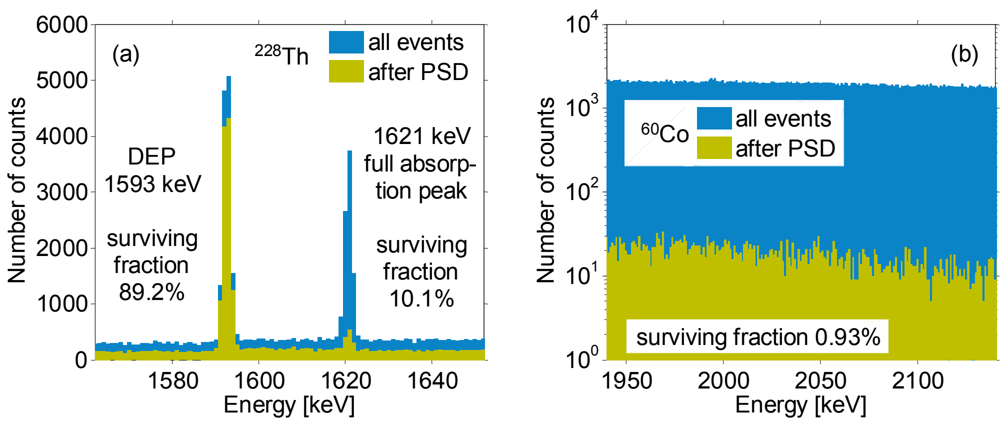

FIGURE 3. Recorded spectra before and after the PSD cut: **(a)** ^{228}Th zoomed on the DEP of the 2.6 MeV line, and the 1.6 MeV FEP of ^{212}Bi; **(b)** ^{60}Co zoomed on the energy region around $Q_{\beta\beta}$.

Conclusions

The presented experimental measurements with a BEGe detector demonstrate its excellent performance to separate single site events from multi-site events via a novel pulse-shape discrimination method. With an 89% acceptance of double-beta decay-like DEP events, significant suppression of most important backgrounds was demonstrated. Especially, γ-ray interactions from a ^{60}Co source located on the detector cap, simulating intrinsic ^{60}Co contamination cosmogenically produced in Ge, were removed on 99% level. The results favourably compare with those achieved with highly segmented detectors [6]. Using unsegmented detectors in low-background experiments has a benefit of removing potential backgrounds coming from additional signal contacts and read-out electronics, which are required for segmented detectors. As a consequence of these favourable characteristics, the BEGe technology was included alongside the detector segmentation in the research and development for the second phase of the GERDA experiment.

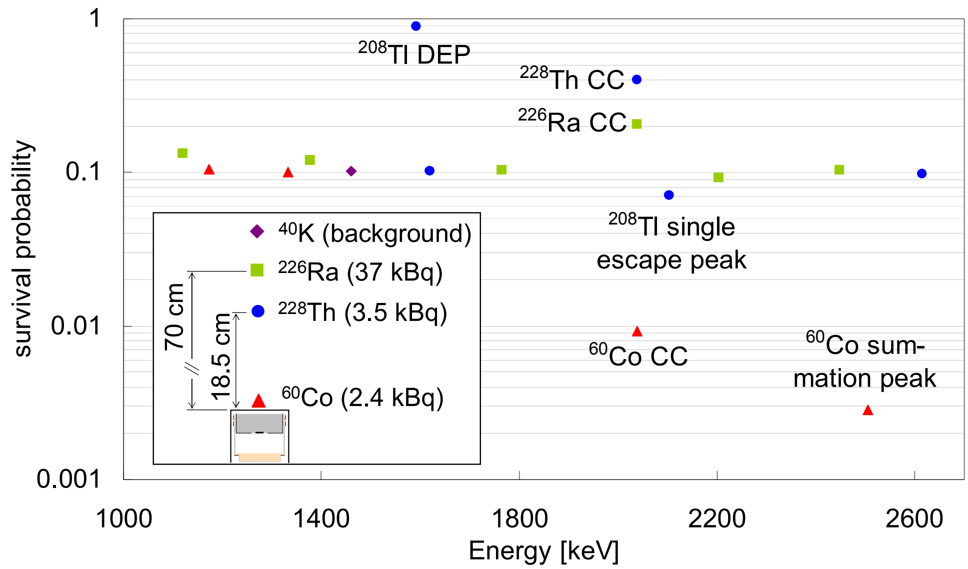

FIGURE 4. PSD cut survival probabilities of spectral peaks, and events from Compton continuum (CC) around $Q_{\beta\beta}$ = 2039 keV. The data points that are not full absorption peaks are labelled.

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