Development of a Pulse-shape-discrimination Method for Identification and Rejection of Alpha Events in High Purity Germanium Detectors

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Abstract. The efficiency of pulse-shape-discrimination (PSD) methods for rejection of α-ray-induced events in high purity germanium detectors of the BEGe-like (BEGe standing for Broad Energy Germanium) type was studied. A high number of α-ray events was obtained by placing a gold foil with deposited ^{209}Po on the $p+$ contact of the detector. Investigated classification methods were trained exclusively on γ-ray events from a ^{228}Th source (using the so-called single-site and multi-site γ-ray events) and applied to α-ray events. The aim of this work was to test if a PSD classifier trained and calibrated solely on γ rays can also efficiently remove α-ray events with no further adaptation. The ROOT/TMVA projective-likelihood estimator, a multi-layer-perceptron (MLP) artificial neural network, and A/E methods were all studied. For the tested BEGe-like detector, the projective likelihood showed the best performance, rejecting α-ray background events by more than a factor of 10^4 (limited by statistics), while maintaining a high survival probability of about 89% for single-site γ-ray events.

INTRODUCTION

Surface contamination of high purity germanium (HPGe) detectors by the long-lived ^{222}Rn daughters, namely ^{210}Po or ^{210}Pb, can produce a serious background source if the detectors are used in searches for rare nuclear processes taking place at low energies. This is the case for searches for neutrinoless double beta ($0\nu\beta\beta$) decay. Emitted by ^{210}Po, α particles can enter the active part of the detectors and deposit all or part (after losing some energy in the inactive layers) of their energies, creating a spectrum that extends from the nominal 5.3 MeV towards lower energies. Some of the decays may then contribute to the signal registered in the $Q_{\beta\beta}$ region of interest (ROI).

In the LEGEND experiment, in order to achieve the background level allowing for measurements of the $0\nu\beta\beta$ half-life of ^{76}Ge at the level of 10^{27} years, the potential α-induced count rate in the ROI must be completely suppressed. The anticipated background index in LEGEND-1000 is $9.1^{+4.9}_{-6.3} \times 10^{-6}$ counts/(keV kg yr) [1]. In such experiments, the expected count rate of α-ray-induced events is very low, and therefore not sufficient for training and calibration of a dedicated α cut. On the other hand, calibration runs with γ-ray emitters, i.e. ^{228}Th, are performed on a regular basis, and therefore provide a high count of γ-ray events for training and calibrating any pulse-shape-discrimination (PSD) cut. We present studies of rejection of α-ray-induced events using multiple PSD-classification methods that were trained exclusively on γ-ray events from a ^{228}Th source. The aim of this work is to test if a PSD classifier prepared in such a way can also efficiently remove α-ray events with no further adaptation.

EXPERIMENTAL SETUP

In order to develop and test efficient methods for identification and rejection of α-particle-induced events, we needed to accumulate a large enough sample of α-ray events. In the studies we used a point-contact semi-planar germanium detector, commonly referred to as broad-energy-germanium-type (BEGe-type), which is schematically shown in Fig. 1. Detailed description of its manufacturing process and characterization can be found in Ref. [2]. In order to collect sufficient statistics of α-ray events, an artificial source was prepared. A round disk with diameter $d = 6\,\text{mm}$ was cut from pure gold foil, and ^{209}Po was deposited on its surface. ^{209}Po emits alphas with energies $E_1 = 4883\,\text{keV}$ (79%) and $E_2 = 4885\,\text{keV}$ (19%). The contaminated gold disk was then installed on the $p+$ contact of the detector to simulate contamination. The detector was installed in a classical vacuum cryostat operated at surface and shielded with 10 cm of lead. A muon-veto detector (plastic scintillator) was placed on top of the lead shield. Detector pulses were recorded directly from the preamplifier using a 100-Mhz 14-bit FADC card. A ^{228}Th calibration source was placed inside the shield for the energy-scale determination and for training of the investigated PSD methods. The calibration spectra also included α-ray events originating from ^{210}Po decays. After acquiring sufficient statistics for PSD

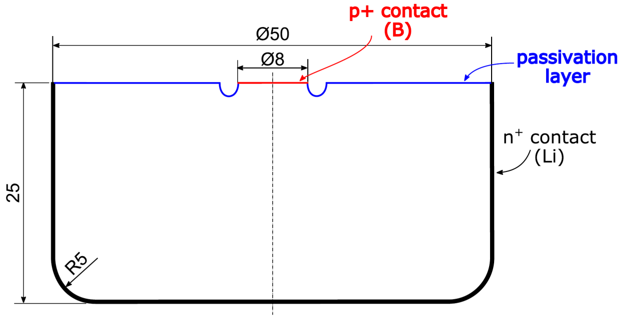

FIGURE 1. Scheme of the detector used in the investigations. The thick black line represents the n+ contact created by lithium thermo-diffusion. The red and blue lines represent the boron-implanted p+ electrode and the passivated surface, respectively. Dimensions are given in mm.

training, about 10,000 single-site and multi-site events from the ^{208}Tl double-escape peak (DEP) and ^{214}Bi full-energy peak (FEP), respectively, were recorded without the calibration source.

ANALYSIS PROCEDURE

In previous works, PSD methods were utilized to reduce the background by discriminating between single-site and multi-site γ-ray events [3, 4]. This is particularly important in the search for hypothetical $0\nu\beta\beta$ decay, because $0\nu\beta\beta$ decay would ionize the germanium by means of two electrons with a range of less than 1 mm in the crystal, thus making it a point-like (or “single-site") event expected to produce a pulse shape very similar to a γ-ray single-site event. Therefore, any multi-site deposition (i.e. Compton-scattered γ-rays) should be rejected by the PSD, reducing the overall background level of the experiment. In case of α particles, the energy is also deposited in a small volume of the detector crystal, as α-rays traveling through germanium lose their energy in a very short distance [5]. Although an α-ray event is also of single-site nature, its energy deposition occurs very close to the detector's passivated surface, leading to a significantly different pulse shape [6]. It is not clear how well a classifier trained to discriminate between single-site and multi-site γ events will fare on α-ray events since they are effectively a third class of events (unknown to the classifier). Therefore, any investigated PSD method must be tested to determine if it will be successful in reducing α-ray events. The projective-likelihood (PL) estimator implemented in the ROOT/TMVA package [7] was our primary candidate for further investigation. PL can provide an effective classification method by rejecting anything outside a designated class of inputs (in this case single-site γ-ray events with characteristic rise time). For reference, two previously used PSD methods were also applied: multi-layer-perceptron (MLP) artificial neural network (ANN), and the A/E classifier [8], where discrimination is based on the ratio of the maximum current amplitude A to the calibrated energy of the event E.

All classifiers were prepared/trained solely with γ-ray events from ^{228}Th, and the cut values were chosen to preserve 90% of events from the 1592.3-keV double-escape ^{208}Tl peak, as described in [3] and applied to α-ray events with no further adjustments. Effectiveness of the selection cut against multi-site γ-ray events is calculated as the survival of the γ-ray events in the ^{214}Bi full-energy peak (FEP). The results of calibrated cuts on various event types in the ^{228}Th spectrum are summarized in Table I. The A/E value is calculated directly, by dividing the maximum current amplitude A by the calibrated energy of the event E, as described in [8]. The input for PL and ANN is prepared by calculating the time t_0 of maximum current for a given pulse, and taking 12 waveform samples before and 8 samples after the t_0 time point. Selected samples are then summed in groups of 4 in order to reduce the number of dimensions. This process is illustrated in Fig. 2 and described in more details in [3] and [4]. Beforehand, all waveforms are normalized according to their calibrated energy.

TABLE I. Survivial of ^{228}Th gamma peaks after various PSD cuts (DEP - *double escape peak*, FEP - *full energy peak*, SEP - *single escape peak*).

Peak	Projective-likelihood cut	ANN MLP cut	A/E cut
DEP 1592.3 keV	89.6 ± 0.7 %	90.4 ± 0.6 %	92.6 ± 0.8 %
FEP 1620 keV	25.6 ± 1.1 %	15.9 ± 0.8 %	17.1 ± 1.0 %
SEP 2103 keV	17.7 ± 0.6 %	9.7 ± 0.5 %	9.9 ± 0.5 %
FEP 2614.5 keV	27.2 ± 0.2 %	13.6 ± 0.1 %	15.9 ± 0.1 %

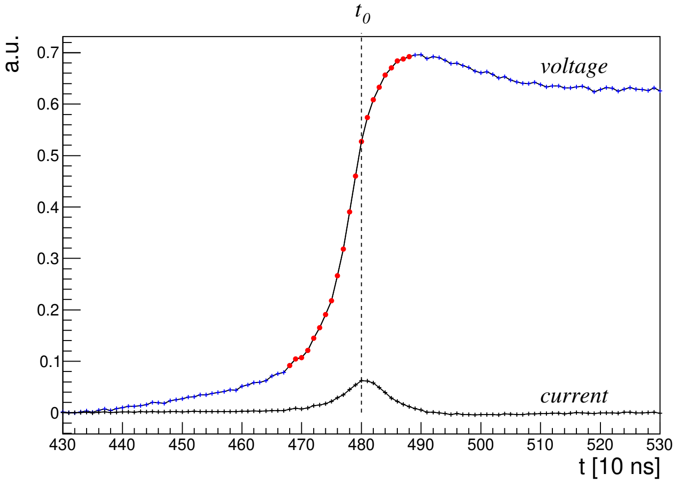

FIGURE 2. Example of PSD input data selection from BEGe pulse shape. For this analysis, twelve samples before and eight samples after t_0 were used (marked as red dots).

RESULTS

Figure 3 shows an energy spectrum acquired with the α-ray source. The most prominent α-ray-induced peak is visible with the observed energy of the peak maximum at $E = 4749 \pm 17$ keV, with the second, smaller one at $E = 5184 \pm 21$ keV. The first peak originates from ^{209}Po deposited on gold, while the latter represents residual contamination with ^{210}Po from previous tests. It should be noted that α-rays emitted by ^{209}Po have nominal energies $E_1 = 4883$ keV and $E_2 = 4885$ keV (the 2-keV difference is below the energy resolution of the utilized detector), and those emitted by ^{210}Po are nominally 5304 MeV. In both cases, the observed peak maxima are shifted by $\Delta E \approx 100$ keV. This effect most likely originates from energy loss in the inactive region of the p+ contact (its thickness is estimated to be about 0.58 µm).

During 30 days of acquisition time, we collected about 10^5 counts of α-ray events for analysis in the energy range of 3500 – 5500 keV. Each pulse-shape-discrimination method was trained/calibrated separately on ^{228}Th γ-ray peaks and applied to the spectrum recorded with only the α-ray sample. The reduction of α-ray events was determined based on all events in the energy range of 3500 – 5500 keV in order to incorporate both the α peaks and their long tails; see Fig. 3. For estimation of residual background (caused e.g. by muons) an independent measurement was performed without the α-ray source. After application of the PSD methods the residual count rate in the energy range of 3500 – 5500 keV was subtracted from the residual count rate of the spectrum with α-ray-induced events (after PSD). The final reduction factor was then calculated as the ratio of the events remaining (surviving the selection cut) in the discussed energy range to all events in the same energy range of the α-ray sample (the muon rate was negligible compared to the α-ray rate). Table II lists the α-ray reduction factors for each cut.

Among the tested methods projective likelihood showed the best performance for α-events rejection. The PL-cut analysis sets an upper limit of no more than 16 α-ray events left (90% C.L.) in the energy range of 3500 – 5500 keV, after PSD and cosmic-background subtraction. This corresponds to an α-ray reduction factor of more than 1.3×10^4 (result is limited by the size of the α-ray induced sample). The same cut retains 89.6% of the single-site γ-ray signals, with 25% survival probability of the multi-site γ-ray signal.

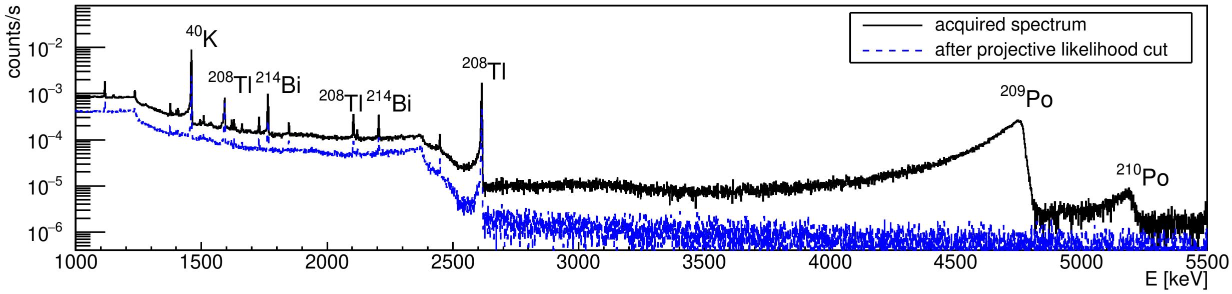

FIGURE 3. Spectrum of acquired events before (black) and after (blue) the projective-likelihood cut. Two prominent α peaks are visible in the high-energy region. The bigger one is from ^{209}Po (gold plate) and the smaller one is from ^{210}Po (surface contamination of the detector). Peaks below 2.6 MeV are from gammas.

The neural network shows very good performance for γ-ray events (90% single-site survivability vs 14% for multi-site). In the energy region from 3500 – 5500 keV there were 123 ± 78 α-ray events left after the selection cut and background subtraction, corresponding to a reduction factor of 1.7×10^3. Additionally, for the artificial-neural-network method, we observed poor α-rejection stability, with network response highly dependant on the input parametrization. This effect is most likely due to the inherent single-site nature making them difficult to distinguish from single-site γ-ray events without training.

The A/E cut performs well for γ-ray events, achieving a 90% survival probability for single-site events while only allowing survival of 17% of multi-site events. Analysis of removal of α-ray events shows 526 ± 52 α-ray events are left after the A/E-selection cut and background subtraction, corresponding to a reduction factor of 4.1×10^3.

TABLE II. α-ray events reduction factors in the energy range of 3500 – 5500 keV after discussed PSD selection cuts. Every cut was analyzed independently.

Projective-likelihood cut	$> 1.3 \times 10^4$
ANN MLP cut	1.7×10^3
A/E cut	4.1×10^3

CONCLUSION

For γ-ray events, the artificial-neural-network classifier usually provides the best result for distinguishing between single-site and multi-site events. However, it does not provide the best available performance for identifying α-ray events, most likely due to their single-site nature. In contrast, the A/E and the ROOT/TMVA projective-likelihood estimator offer good performance for muon and multi-site γ-ray reduction and can also filter out α-ray events very well with the same rejection cut. Within tested statistics, the PL method offered the best performance for rejecting α events, while showing slightly lower efficiency for rejecting multi-site events. The overall performance for PL is however very good, especially taking into account that only one selection cut is applied.

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