A novel method for improving rise-time resolution in pPCGe detectors at sub-keV energies

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Introduction

The state-of-the-art p-type point-contact Germanium detector (pPCGe) technology, characterized by its superior background rejection, sub-keV energy threshold, and excellent energy resolution, has become an ideal tool for investigating low-energy rare physics events, in particular neutrinos and dark matter [1]. Nevertheless, the pPCGe is subject to irregular behavior caused by surface effects for events near the passivated surface (comprises Li-diffused n^+ conductive contact and typically $\mathcal{O}(1\text{ mm})$ thickness) known as transition layer that feels weaker than the applied electric field, leading to slower pulses and poor charge collection, which ultimately reducing the ionization yield. The relatively slower pulse rise-time at the surface distinguish them from those in the Ge crystal bulk.

A typical sample of bulk and surface events at 250 eV_{ee} energy is presented in the top panel of Fig. 1, along with the pulse rise-time characteristics smooth-fit by a hyperbolic tangent function [2]. This method of measuring pulse rise-time is particularly effective at higher energies for distinguishing surface events from bulk signals. However, as we approach the energy threshold, the resolution of the rise-time measurement declines, resulting in overlapping rise-time distributions of bulk and surface events, as evident in the two dimensional parameter space shown in the bottom panel of Fig. 1.

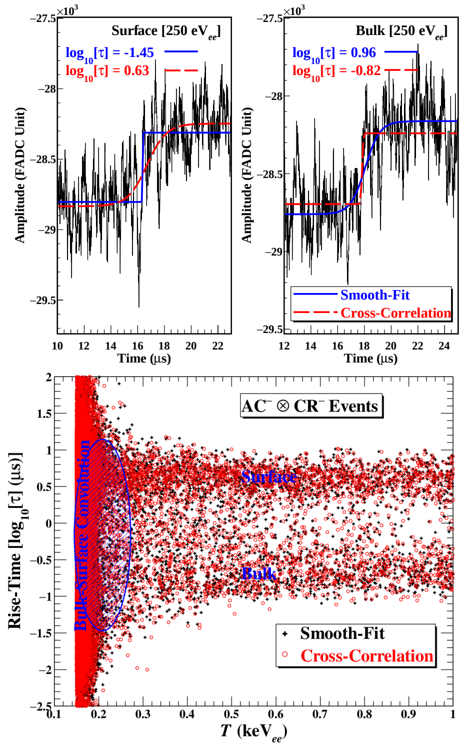

FIG. 1: (Top) Typical bulk (left) and surface (right) pulses at 250 eV_{ee} measured with the pPCGe detector are displayed, along with the smooth-fit and cross-correlation. (Bottom) The two-dimensional distribution of rise-time ($\log_{10}[\tau]$) versus energy, obtained with uncorrelated $AC^-\otimes CR^-$ (Anti-Compton-Veto⊗Cosmic-Ray-Veto) events in the pPCGe detector.

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Our study aims to resolve the bulk-surface convolution by improving rise-time resolution at near threshold energies with cross-correlation shape-matching, as shown by the dashed line in the top panel of Fig. 1.

Methodology

A notable aspect of multi-parameter fits, including the hyperbolic tangent fit [2] (smooth-fit), is their dependence on the initial parameter settings, i.e. seeding, playing a crucial role. Among them, the seed for the time offset t_0 is particularly influential, thus our initial focus is on evaluating the pulse time offset via shape-matching.

Utilizing certain a priori assumptions or prior information about the *signal pulses*, a *reference pulse shape* can be constructed for matching with real data. We have employed an optimized NI PXI-5412 test pulser module to test this idea. The best match between the reference shape and the data provides the time offset estimate, corresponding to the t_0 of the reference shape. The similarity metric for matching can be determined by the cross-correlation of the signal pulse and the reference shape, as described by

$$\mathcal{CC}(\Delta t_D^{\mathcal{R}}) \equiv \int_{t_i+\Delta t_D^{\mathcal{R}}-\frac{W}{2}}^{t_i+\Delta t_D^{\mathcal{R}}+\frac{W}{2}} \mathcal{R}(t-\Delta t_D^{\mathcal{R}}) \cdot \mathcal{S}(t)\mathrm{d}t \ . \tag{1}$$

Here, $\mathcal{CC}$ denotes the cross-correlation value, $\Delta t_D^{\mathcal{R}}$ is the time displacement of the reference shape from an initial time t_i, and W is the integration window's width. $\mathcal{R}$ and $\mathcal{S}$ represent the reference shape and signal pulse, respectively. The reference shape is scanned across various t_0 values, given by $t_i + \Delta t_D^{\mathcal{R}}$, assuming it is positioned at the center of the integration window. An analysis of Eq. 1 demonstrates that the $\mathcal{CC}$ between two hyperbolic tangent functions is maximized when their t_0 parameters are aligned. This observation leads to the conclusion that the optimal estimate for t_0 corresponds to the position of the $\mathcal{CC}$ peak.

Performance and prospects

Enhanced estimation of the pulse time offset t_0 through the cross-correlation method, as opposed to the current smooth-fit method [1], influences the overall rise-time analysis, which is illustrated with real data in Figs. 1 and 2.

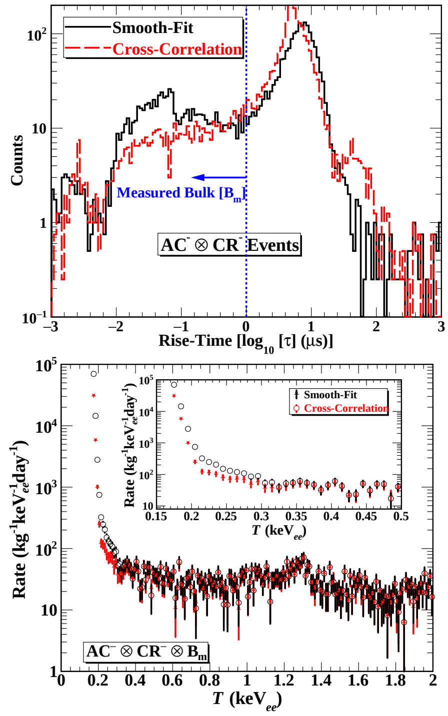

FIG. 2: (Top) The one-dimensional rise-time distribution of the same events within energy range 140-300 eV_{ee} is depicted using both smooth-fit and cross-correlation methods. (Bottom) The energy spectrum of selected bulk events [$AC^- \otimes CR^- \otimes B_m$] (where $\log_{10}[\tau] < 0.0\ \mu$s) is included for comparison.

Effective pulse identification (bulk and surface) through cross-correlation leads to a notable decrease in noise events (from the chosen crystal bulk region) relative to the smooth-fit approach. This reduction significantly suppresses background in the sub-keV region and enhances the accuracy of uncertainty measurements. Presently, we are exploring its potential to reduce noise events further, which may facilitate a reduction in the noise-edge detection threshold.

References

[1] H.B. Li *et al.*, *Astroparticle Physics* **56**, 1 (2014); L.T. Yang *et al.*, NIM **A 886**, 13 (2018).

[2] M.K. Singh *et al.*, Chinese Journal of Physics **58**, 63 (2019).