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Bulk and surface event identification in p-type germanium detectors

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The p-type point-contact germanium detectors have been adopted for light dark matter WIMP searches and the studies of low energy neutrino physics. These detectors exhibit anomalous behavior to events located at the surface layer. The previous spectral shape method to identify these surface events from the bulk signals relies on spectral shape assumptions and the use of external calibration sources. We report an improved method in separating them by taking the ratios among different categories of *in situ* event samples as calibration sources. Data from CDEX-1 and TEXONO experiments are re-examined using the ratio method. Results are shown to be consistent with the spectral shape method.

1. Introduction

The p-type point-contact germanium detectors (*p*Ge) [1,2] possess the merits of low intrinsic radioactivity background and excellent energy threshold in the sub-keV energy range. They have been used in rare-event detection experiments, such as the search of light Weakly Interacting Massive Particles (WIMPs) with mass range 1 GeV $< m_\chi <$ 10 GeV, searches of solar and dark matter axions [3], as well as studies of neutrino electromagnetic properties and neutrino–nucleus coherent scattering with reactor neutrinos [4–6].

Anomalous excess events from the CoGeNT experiment with *p*Ge [7–9] have be taken as signatures of light WIMPs. This interpretation is contradicted by the CDEX-1 experiment at China Jinping Underground Laboratory [10–12] and the TEXONO experiment at the Kuo-Sheng Reactor Neutrino Laboratory [13,14], also using *p*Ge as target.

Central to the discussion is the treatment of anomalous behavior of surface events in *p*Ge [14–17], incorrect or incomplete correction of these effects may lead to false interpretation of the data and limit the experimental sensitivities. The analysis of anomalous surface events and the differentiation between bulk and surface events (BSD) in *p*Ge is therefore crucial to realize the full potentials of this novel detector technique.

The anomalous surface events were studied with the “spectral shape method” in an early work [14]. However, there are several inadequacies with this approach. In this article, we report an improved “ratio method” to address these deficiencies, in which *in situ* data provide additional important constraints and information.

The article is organized as follows. The physics of anomalous surface events in *p*Ge detectors is described in Section 2. The features of uniformity of measured rise-time distributions among different event samples are discussed in Section 3. The spectral shape method is summarized in Section 4, followed by detailed discussions on the ratio method in Section 5. The application to the published data and comparison of their results are discussed in Section 6.

We follow the notations of earlier work [11,12,14], where AC and CR denote the anti-Compton detector and the cosmic-ray veto systems,

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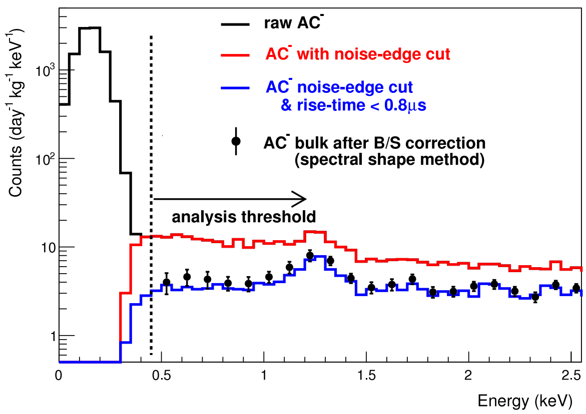

Fig. 1. AC$^-$ spectra of CDEX-1 experiment at various stages [12]: before performing noise-edge cut, after noise-edge cut, spectrum after noise-edge cut and event selection by $\tau <$ 0.7 μs, spectrum after noise-edge cut and B/S correction of spectral shape method (described in Section 4) It shown that the noise-edge is around 350 eV, the analysis threshold in this article is set at 450 eV.

respectively, while the superscript −(+) corresponds to anti-coincidence (coincidence) with the *p*Ge signals. Neutrino- and WIMP-induced candidate events would therefore manifest as AC$^-$ and CR$^-$ ⊗ AC$^-$ in the CDEX-1 and TEXONO data, respectively.

AC$^-$ spectra of CDEX-1 at various stages of event selection are shown in Fig. 1.

2. Anomalous surface events in *p*Ge detectors

The anomalous surface charge collection effect in *p*Ge was noted in early literature [6]. Recent interest of adopting the *p*Ge techniques in dark matter experiments gives rise to thorough studies [14–16].

The n^+ surface electrodes of *p*Ge are fabricated by lithium diffusion and have a typical thickness of ∼1 mm [15,18]. Electron–hole pairs produced at the surface (S) layer in *p*Ge are subjected to a weaker drift field than those in the bulk volume (B). A fraction of the pairs will recombine while the residuals will induce signals which are weaker and slower than those originated in B. The S-events would therefore exhibit slower rise-time and partial charge collection compared to B-events. The charge collection efficiency as a function of the depth of the surface was recently measured and simulated [19]. The n-type point-contact germanium detectors, having micron-sized p^+ surface electrode due to boron-implantation, do not exhibit anomalous surface events [6].

Electronic signals are induced by the drifting charges. The signal rise-time (τ) can be parametrized by the hyperbolic tangent function

$$\frac{1}{2}\, A_0 \times\ \tanh(\frac{t-t_0}{\tau})\ +\ P_0, \qquad (1)$$

where A_0, P_0 and t_0 are the amplitude, pedestal offset and timing offset, respectively. Typical examples of B- and S-events, showing both their raw pulses and the fitted-profiles, at 2 keV and 0.5 keV, are illustrated in Figs. 2a, b, c&d, respectively. A typical rise-time versus energy scatter plot is shown in Fig. 3.

At high energy where S/N ≫ 1, the fits are in excellent agreement with data indicating that Eq. (1) is an appropriate description of the rise-time of physics events. However, at low energy (< 2 keV) where the signal amplitude is comparable to that of electronic pedestal noise, the B- and S-events could be falsely identified, giving rise to cross-contaminations. Software algorithms have to be applied to account for and correct these effects.

Typical pulses at energy near threshold are depicted in Figs. 2c&d. The analysis threshold of 450 eV is well above the RMS of pedestal noise of 62 eV and measurable noise-edge of 350 eV, as shown in Fig. 1. Assuming one exponentially decreasing noise contribution the fraction of noise events is < 1% at 450 eV.

3. Rise-time uniformity

The validity of the software algorithms discussed in this article to differentiate bulk and surface events stands on the uniformity of τ-distributions among both electronic and nuclear recoil events in describing the data to the desired level of accuracy.

Events produced by different particles (electrons, gammas, neutrons) exhibit similar bulk rise-time distributions in Ge detectors with the current generation of technology. Previous work indicated no difference of bulk rise-time distributions for γ-sources and nuclear recoil [20], and recent work reported that electron and nuclear events may differ in their rise-time by about ∼10 ns due to plasma effects [21], much faster than the typical Ge detectors rise-time of ∼1 μs. Differentiation of these signals are at the forefront of research, the success of which would represents a major advance in Ge-detector techniques and applications.

Bulk electron and nuclear recoil events are therefore indistinguishable from their rise-time distributions in Ge ionization detector [20]. Accordingly, rise-time distributions are the same at different B-regions while different depth in S-layers give different rise-time distributions due to the difference in diffusion time of electrons in the surface-inactive regions to the bulk-drifting volume [6,12,14]. The consequences of both are that the rise-time distributions are: (a) uniform for B-events for all sources while (b) different for S-events due to different event-depth distributions for sources of different energy.

Non-uniformity of surface rise-time distributions is corrected by calibration sources selection, as discussed in details in Section 6.1. The selection is data/experiment dependent, not universally applicable to all analysis.

The understanding of nature of rise-time distributions is beyond the scope in this analysis. An *ab initio* approach by simulation of behavior of particles in *p*Ge and configuration of *p*Ge would provide an alternative way to understand and address the B/S issue, though the current accuracies do not match the data-driven approaches discussed in this article.

4. Bulk-surface differentiation: Spectral shape method

The spectral shape method is a cut-based algorithm [14] developed to perform BSD for light WIMP searches with the CDEX-1 [11,12] and TEXONO [13] data.

Two parameters have to be derived: the B-signal retaining and S-background suppression efficiencies, denoted by ϵ_{BS} and λ_{BS}, respectively. The efficiency-corrected "real" B- and S-rates (B_r, S_r) are related to measured rates (B_m, S_m) via:

$$\begin{aligned} B_m &= \epsilon_{BS} B_r + (1-\lambda_{BS}) S_r \\ S_m &= \lambda_{BS} S_r + (1-\epsilon_{BS}) B_r, \end{aligned} \qquad (2)$$

with an additional unitary constrain of $B_m + S_m = B_r + S_r$.

The solutions of Eq. (2) are:

$$\begin{aligned} B_r &= \frac{\lambda_{BS} B_m - (1-\lambda_{BS}) S_m}{\epsilon_{BS} + \lambda_{BS} - 1} \\ S_r &= \frac{\epsilon_{BS} S_m - (1-\epsilon_{BS}) B_m}{\epsilon_{BS} + \lambda_{BS} - 1}. \end{aligned} \qquad (3)$$

Two components contribute to $B_r(S_r)$. The first positive term accounts for the loss of efficiency in the measurement of $B_m(S_m)$, while the second negative term corrects misidentification due to contamination effects. Both (ϵ_{BS}, λ_{BS}) factors should be properly accounted for in order to provide correct measurements of the energy spectra for bulk events.

In order to solve Eq. (2) for the two unknown parameters (ϵ_{BS}, λ_{BS}), at least two sources with different but known B- to S-event ratio are required. Four calibration sources (^{137}Cs, ^{241}Am, ^{57}Co and ^{60}Co) [11,12] were used in CDEX-1 analysis. The B_r spectra of these sources were evaluated by full GEANT4 simulation, so that (ϵ_{BS}, λ_{BS}) were derived having the corresponding measured B_m. The WIMP candidate data and ambient gamma background were then corrected by ϵ_{BS} and λ_{BS}.

However, there are several deficiencies with the spectral shape method: