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Laboratory tests of pulse shape discrimination techniques for correcting the effects of radiation damage in germanium coaxial detectors

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Abstract

A reverse-electrode closed-end germanium coaxial detector was irradiated with 183-MeV neutrons to evaluate the value of Pulse Shape Discrimination (PSD) techniques in restoring the energy resolution and line shape of the radiation damaged detector. Two consecutive irradiations were performed for total fluences of 5.0×10^{8} and 10.4×10^{8} n/cm^{2}, with PSD tests performed after each irradiation. These irradiations degraded the energy resolution and line shapes; however, PSD corrections significantly restored the performance, even after severe damage. These PSD techniques delay and potentially eliminate, in some experimental situations, the need to anneal germanium detectors in damaging radiation environments.

Keywords: Germanium; Detectors; Gamma-ray; Radiation damage

1. Introduction

Current pulses from Germanium Detectors (GeDs) are usually integrated to determine the total energy deposited in the detector; however, the shapes of the current pulses depend on the location, magnitude and number of individual energy depositions. By utilizing Pulse Shape Discrimination (PSD) techniques, much of this information can be extracted and used to enhance the detector performance. A detailed description of our PSD algorithms and their use in beta-decay background rejection are given elsewhere [1].

We are investigating PSD techniques to correct for the effects of radiation damage in GeDs. While we are motivated by space applications, where cosmic rays, solar flare particles, terrestrial trapped particles, and their secondaries cause damage, these techniques can be applied to detectors in any damaging radiation environment. The resulting

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damage degrades spectral resolution over time, diminishing the sensitivity of GeDs to gamma-ray flux and line shape measurements. Radiation damage overwhelmingly creates hole traps in GeDs [2], which decreases the *charge collection efficiency* – the fraction of the initial free charge produced by an energy deposition that is actually measured on the signal electrode – more for events near the central bore than near the outer electrode in reverse-electrode coaxial GeDs.

Numerical simulations have indicated that PSD techniques could correct for the effects of radiation damage [3]. The measurable time to peak of the current signal for a single-site event is roughly proportional to the radial position of the interaction [1]. We define the time to peak dependence of the charge collection efficiency as the charge collection efficiency curve (CCEC). Using our current PSD techniques, multiple-site photon events can be statistically separated into the two effectively largest fractional energy depositions and corresponding times-to-peak, and then each fractional energy deposition corrected separately for trapping using the CCEC to get a corrected total energy. Since gamma-ray events are generally complex, with more than two interaction sites per total energy deposit, this two-site correction is a statistical correction to the overall charge collection given the overall current pulse shape, as opposed to an explicit correction for each individual interaction. In principle, these techniques can be used to correct for any effects that vary the charge collection efficiency with time to peak, including hole trapping, electron trapping, and ballistic deficit. To verify the numerical simulations, we irradiated a GeD with 183 MeV neutrons and evaluated our PSD techniques for correcting the effects of the damage.

2. Experimental setup and measurements

For this experiment we used a long, 79.8 mm, reverse-electrode closed-end coaxial GeD, with an outer diameter of 57.0 mm. To improve PSD performance [1], the central bore is unusually narrow, 5.5 mm diameter, and extends 70 mm into the detector. The depletion voltage is -3200 V, and the GeD was operated at -4000 V for these tests. The detector temperature was held at 82 K both during irradiation and continuously afterwards to minimize the effects of temperature cycling, which can significantly worsen the effects of the radiation damage [4].

The detector was irradiated with 183 MeV neutrons in two consecutive stages at the Polarized Neutron Facility of the Indiana University Cyclotron Facility [5]. The goal was to achieve moderate damage in the first irradiation and severe damage in the second. The fluence of the first irradiation was $(5.0 \pm 0.2) \times 10^8$ n/cm^2, while the second irradiation brought the total fluence to $(10.4 \pm 0.3) \times 10^8$ n/cm^2.

We used PSD electronics developed for the HEXAGONE balloon experiment [6], modified to perform as our electronics currently under development [7] for the European Space Agency's International Gamma-Ray Astrophysics Laboratory (see discussion below). Current signals from the detector were collected on a slow channel (4 μs peaking time) to measure the total charge (energy) signal, as well as on a parallel fast channel (20 ns shaping time) that was sampled in 10 ns intervals by an analog-to-digital converter to digitize the current pulses with 9-bit precision.

We measured the CCECs with the single-site line events produced using the 1.593 MeV double escape peak of a ^{228}Th source. Separating the events by the current pulse time to peak and binning them to form separate line spectra (Fig. 1), the relative charge collection efficiency was determined by comparing the line centroids for each separate time to peak. The CCECs for the moderately damaged detector (Fig. 2a) and the severely damaged detector (Fig. 2b) clearly show the strong effects of hole trapping for the fast time-to-peak events (near the central bore), while there is little effect on the long time-to-peak events. Note that since our techniques only measure the relative charge collection efficiency for different times to peak, the overall normalization is unknown. However, only the relative efficiencies are needed for correction. For convenience we have normalized each curve to unity at the time to peak with the highest charge collection efficiency – consequently the overall normalizations in these curves are not the same. The changes in the CCECs after each

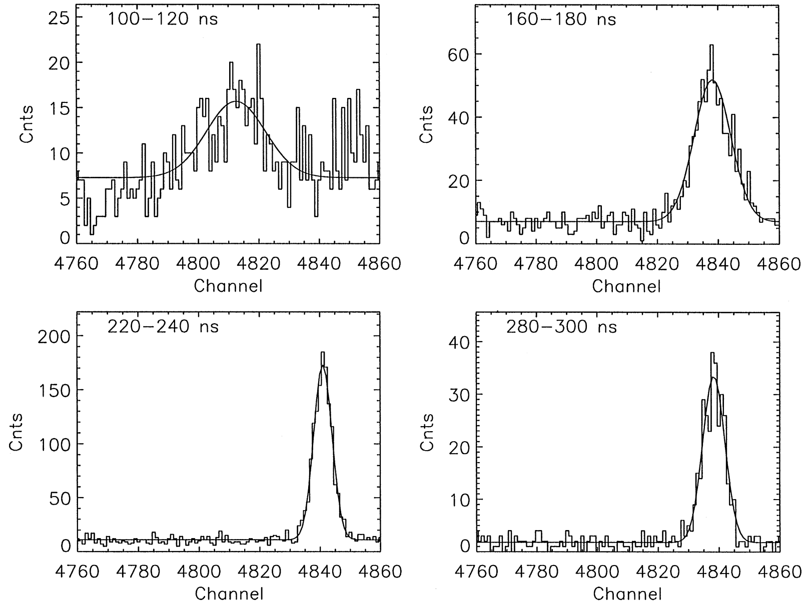

Fig. 1. The 1.593 MeV spectral line shapes measured from the severely damaged detector, binned by the times to peak given in each panel. Gaussian fits were made to determine the line centroid channel for each time to peak range.

irradiation are consistent with radiation damage creating predominantly hole traps.

3. PSD correction results

We use three parameters to characterize the spectral line shapes. The full-width at half-maximum (FWHM), and full-width at tenth-maximum (FWTM) are the traditional parameters used to characterize the overall shape of the spectral response. Here we also use the effective FWHM (EFWHM), defined as the width of the central peak that contains 76% of the counts, which would equal the FWHM for a perfect Gaussian line shape. Astrophysical observations of gamma-ray lines are almost always background dominated, and in these cases the sensitivity of a detector to narrow lines depends more closely on the EFWHM than the FWHM, since the EFWHM accounts for both the line broadening and the overall shape. For radiation damaged reverse-electrode GeDs, the EFWHM degrades faster than the FWHM due to the movement of counts from the central peak into the low-energy tails.

The measured spectral parameters for the 1.333 MeV line from ^{60}Co before irradiation are presented in Table 1. The ratio of FWHM to FWTM, and the EFWHM to FWHM are consistent with a Gaussian line shape. However, the FWHM from the undamaged detectors measured with our PSD electronics (2.48 keV, 4 μs peaking time) is broader than measured from the same detector using electronics with longer peaking times ($\sim$ 2.0 keV, $\sim$ 8 μs peaking time). This difference is most likely due to ballistic deficit caused by the relatively short peaking time of the PSD electronics. While undesirable, the short peaking time does not affect our basic overall conclusions.

The spectral line at 1.333 MeV after moderate radiation damage, 5.0×10^8 n/cm^2 total fluence, is shown in Fig. 3a, with spectral characteristics presented in Table 1. The line is slightly broader with a moderate low-energy tail compared to the undamaged spectrum. The FWHM has shown only a slight increase of 2%, while the FWTM a much more significant increase of 60%; however, the EFWHM has shown a large increase of 83%.

The same spectral line after severe radiation damage, 10.4×10^8 n/cm^2 total fluence, is shown in

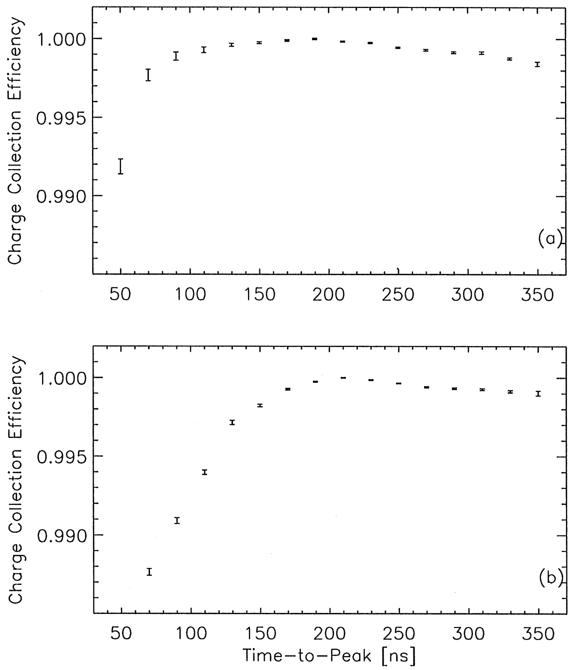

Fig. 2. Charge collection efficiency curves (CCEC) measured with the 1.593 MeV double escape peak produced with a ^{228}Th source (single-site events) for the (a) moderately damaged detector, and (b) severely damaged detector. The effects of the radiation damage dominate for events near the central bore (smaller times to peak), consistent with hole trapping.

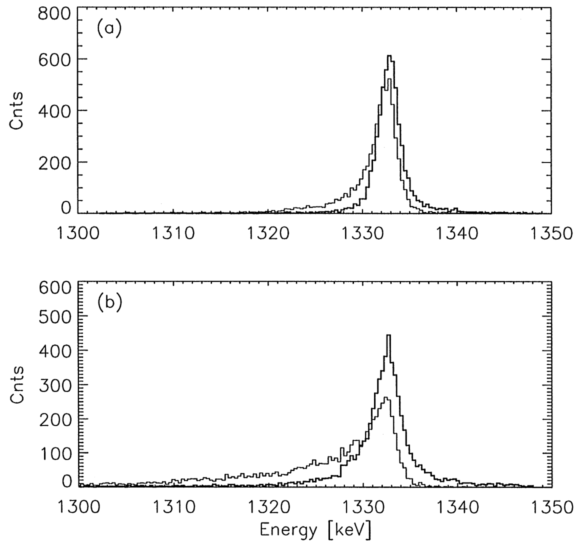

Fig. 3. Measurements of the 1.333 MeV ^{60}Co spectral lines. For the moderately damaged detector (a), both the uncorrected line shape (thin) and the corrected line shape (bold) are shown for comparison. The same is true for the severely damaged detector (b). PSD correction has restored many of the counts in the low-energy tails to the central peak.

Fig. 3b, with spectral characteristics presented in Table 1. The line is much broader with a severe low-energy tail compared to the undamaged spectrum. Quantitatively, the FWHM and FWTM have shown drastic broadening, 42% and 245%, respectively; furthermore, the EFWHM has shown a whopping increase of 378%.

The measured CCECs for the moderately damaged detector (Fig. 2a), and severely damaged detector (Fig. 2b) were used in combination with PSD as described above to correct for the radiation damage. The resulting 1.333 MeV spectral lines are shown in Figs. 3a and b, respectively, with parameters presented in Table 1. For the moderately damaged detector, the FWHM has been restored to the undamaged value, while the FWTM has been reduced to an increase over the undamaged of 20%. The EFWHM has been improved to a 39%

Table 1
Measured spectral line performance at 1.333 MeV

Fluence (10^8 n/cm^2)	PSD	Pulser FWHM (keV)	1.333 MeV line FWHM (keV)	FWTM (keV)	EFWHM (keV)	SNR
0	No	1.10	2.48 ± 0.02	4.58 ± 0.04	2.51 ± 0.02	1.00
5.0	No	1.18	2.52 ± 0.02	7.31 ± 0.07	4.59 ± 0.04	0.74
5.0	Yes	—	2.46 ± 0.02	5.44 ± 0.05	3.49 ± 0.03	0.86
10.4	No	1.19	3.51 ± 0.03	15.82 ± 0.15	12.01 ± 0.11	0.46
10.4	Yes	—	2.96 ± 0.03	9.03 ± 0.08	6.82 ± 0.06	0.62

increase over the undamaged detector, reducing the effects of the damage by half. For the severely damaged detector, the FWHM and FWTM have been improved to 19% and 97% increases over the undamaged case, respectively, while the EFWHM has been improved to a 172% increase, once again reducing the effects of the radiation damage by half.

While a detailed comparison with previous PSD methods is not possible (see Ref. [3] for summary), our measurements and simulations support the assertion that the two-site correction technique provides roughly a factor of two improvement in correction ability over previous single-site/analog correction techniques.

4. Discussion

Our group has developed PSD techniques to reduce the instrumental background [7,1] for the array of 19 closed-end coaxial GeDs on the European Space Agency's International Gamma-Ray Astrophysics Laboratory [8]. PSD can also be used to correct for radiation damage in these detectors. Astrophysical observations of gamma-ray lines are almost always background dominated, in which case the signal-to-noise ratios (SNRs) are proportional to the inverse of the square root of the EFWHM. PSD correction improves the EFWHM of the line, returning counts from the low-energy tail to the peak, significantly improving the SNRs. In Table 1 the SNRs are presented, normalized to 1.0 for the undamaged detector. PSD correction roughly decreases the effects of radiation damage by half, doubling the operating life (possibly as long as the mission lifetime) for GeDs in space before requiring risky, often complex annealing to recover from radiation damage.

Since our PSD techniques have been optimized for background rejection, not for radiation damage correction, these results are lower limits on PSD correction for radiation damage. For example, improving the resolution on times to peak for events near the central bore, where the CCECs are changing most rapidly, could improve the technique significantly. The current time-to-peak resolution is set by the 10 ns library binning; however, interpolation between the sampled points could potentially improve the resolution to ~ 1 ns. Other modifications that could significantly improve the technique include fitting the current pulses to more than two depositions, and discriminating and correcting events in the closed-end section of the detector separately.

Thus far, we have not addressed how to create an energy correction curve for an actual detector on a satellite instrument. While most of the background counts are single-site beta-decay events, these events are part of the continuum – single-site counts from a narrow line were used to produce the charge collection efficiency curves in this work. One empirical method to derive the CCEC would be to use numerical relaxation techniques and an initial estimate of the CCEC to find the curve that produces the smallest EFWHM. If there are no strong double escape lines in the background, then multiple-site photon events can be used for a first estimate of the CCEC. We found that the multiple-site photon CCECs slightly underestimate the effects of trapping on the shorter times to peak relative to the true single-site CCECs, as is expected since the secondary photon interaction sites preferentially occur toward larger radii in the detector. However, these photon CCECs are quantitatively similar, and could serve as good first estimates of the true single-site CCECs.

Our PSD techniques clearly diminish the energy resolution degradation due to radiation damage in coaxial GeDs. The ability to derive CCECs and their use in combination with PSD to perform two-site correction is clearly demonstrated. These results agree well with numerical simulations [3].

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