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Fast Digitization and Discrimination of Prompt Neutron and Photon Signals Using a Novel Silicon Carbide Detector

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ABSTRACT

Current requirements of some Homeland Security active interrogation projects for the detection of Special Nuclear Material (SNM) necessitate the development of faster inspection and acquisition capabilities. In order to do so, fast detectors which can operate during and shortly after intense interrogation radiation flashes are being developed. Novel silicon carbide (SiC) semiconductor Schottky diodes have been utilized as robust neutron and photon detectors in both pulsed photon and pulsed neutron fields and are being integrated into active inspection environments to allow exploitation of both prompt and delayed emissions. These detectors have demonstrated the capability of detecting both photon and neutron events during intense photon flashes typical of an active inspection environment. Beyond the inherent insensitivity of SiC to gamma radiation, fast digitization and processing has demonstrated that pulse shape discrimination (PSD) in combination with amplitude discrimination can further suppress unwanted gamma signals and extract fast neutron signatures. Usable neutron signals have been extracted from mixed radiation fields where the background has exceeded the signals of interest by >1000:1.

Keywords: SNM, active inspection, silicon carbide, digitization, pulse shape discrimination

1. INTRODUCTION

When photons or neutrons are utilized to interrogate fissionable material, emitted radiation is in the form of prompt and delayed neutrons and photons. The fission process immediately liberates photons and neutrons in $<10^{-14}$ sec after interaction with the stimulating source radiation. There is strong evidence that these actively-produced prompt radiations can have distinguishable characteristics to facilitate nuclear material detection and identification. Prompt thermal neutron-induced fission neutrons will accompany and follow the fast neutron-induced prompt radiations on a time scale that is determined by the capture rate of the thermal neutrons, usually hundreds of microseconds. Delayed neutrons and photons are also emitted from the neutron rich daughters and unstable fission products. These delayed products are emitted on timescales of milliseconds to several seconds after the fission process and in much less abundance than the prompts.

Since prompt emission rates are typically several orders-of-magnitude greater than delayed emission rates (originating long after the prompt effects have subsided), utilization of this prompt emission regime can considerably decrease detection times, increase inspection throughput rates, increase detection sensitivities, and decrease the delivered dose rates during an inspection. A novel detector originally developed by Westinghouse[1-5] for nuclear power reactor monitoring possesses many unique characteristics which make it attractive for active inspection scenarios.

Silicon carbide (SiC) detectors are a relatively new class of radiation detector. They are composed of doped layers of SiC sandwiched between two metal contacts. Depending on the applied voltage, depletion regions of 10-100 μm can be induced having band gaps on the order of 3.25 eV. Incident, ionizing radiation generates ion-hole pairs that are pulled apart under an applied electrical field, creating a current which is amplified and can be recorded. Important advantages of SiC detectors include: ultra-fast response (risetimes of <1 to a few ns); ability to process at high count rates; operable during and within nanoseconds of an intense neutron or photon pulse, and photon insensitivity.

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Due to the exceptionally short duration of the pulse, however, the necessary electronics to measure and process large numbers of signals has not been readily available. To date, therefore, the bulk of the gamma suppression has been accomplished simply through amplitude discrimination. While this is an effective approach pulse shape discrimination (PSD) can provide a more robust method for the discrimination and identification of specific particle types in mixed fields. Recent advances in high-bandwidth, large dynamic range digitization have resulted in commercially available products that can acquire continuous streams of data at rates up to 8 GSamples/s with up to 10 bits of accuracy. Resolution down to 125 ps has enabled the investigation of the nature of the pulse shape from SiC diodes when exposed to different radiation types.

2. INITIAL DEMONSTRATIONS OF PULSE SHAPE DISCRIMINATION

Initial experiments exploring the possibility of separating gamma and neutron signals based on PSD were conducted at INL using low-activity ^{252}Cf (5×10^4 n/s), ^{137}Cs (100µCi), and ^{60}Co (100µCi) sources. In order to reduce the SiC detector capacitance and produce fast rise-time pulses, a reverse bias of -900 V was applied to the detectors such that the SiC diode detectors were fully depleted to 100 µm. A 100-µm polyethylene proton-recoil converter foil was placed adjacent to the detector.[4] The SiC detector output was fed to an Ortec VT120 fast preamplifier leading directly to a digitizer, which collected and digitized the signals at a rate of 8 GSamples/s with an accuracy of 10 bits. The initial attempts at PSD simply identified the pulses and calculated the risetime of the leading edge of the pulse based on a 10%-90% (of peak) transition. That data was stored along with the pulse height, original signal, timing information and collection parameters.

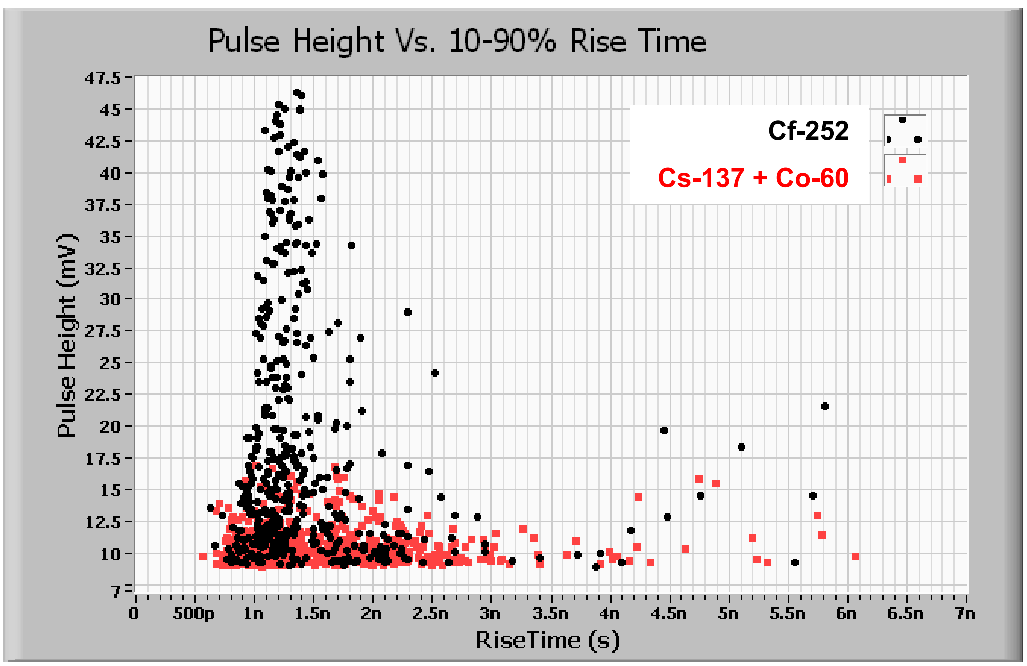

Figure 1. Results of early pulse discrimination work utilizing ^{252}Cf, ^{60}Co and ^{137}Cs.

Illustrated in Figure 1 are results from initial discrimination tests which verified the efficacy of fast digitization coupled with real-time software processing. The signals from the gamma sources were found to span a range of risetimes from less than one nanosecond to over 6 ns. The ^{252}Cf events, however, fall into a reduced band of risetimes (750 ps – 1.75 ns). For the most part, the ^{252}Cf events fall into a region centered around 1.25 ns. Signals outside this range likely result from the Cf decay gamma emissions, spontaneous fission gammas, and gammas resulting from interactions with neutrons. A separate item of note is that the bulk of the gamma signals from the cesium and cobalt sources had a pulse height of less than 12.5 mV, and none had a height of more than 17.5 mV. With the Cf source, however, there are some points which fall outside of the well defined “neutron” band centered around 1.25 ns that do have pulse heights larger than 20 mV. While these could simply be noisy or anomalous signals, it is possible that they could result from less common neutron induced reactions.

3. FURTHER DEVELOPMENT OF THE PSD ALGORITHM

Based on the promising initial results, subsequent tests were performed at Idaho National Laboratory's Health Physics Instrumentation Laboratory (HPIL) and the hot cell at Westinghouse utilizing much stronger sources. HPIL is a National Institute of Standards and Technology (NIST) traceable facility which allows for the exposure of detectors to extremely well characterized and calibrated neutron and gamma fields. The ^{137}Cs, ^{60}Co, and ^{252}Cf sources at HPIL can provide dose rates of up to 828 R/hr, 510 R/hr, and >500 Rem/hr respectively. The sources used at Westinghouse included a 7.5×10^6 n/s AmBe and a 28 Ci ^{60}Co source (10^8 photons/c/sec at the detector location).

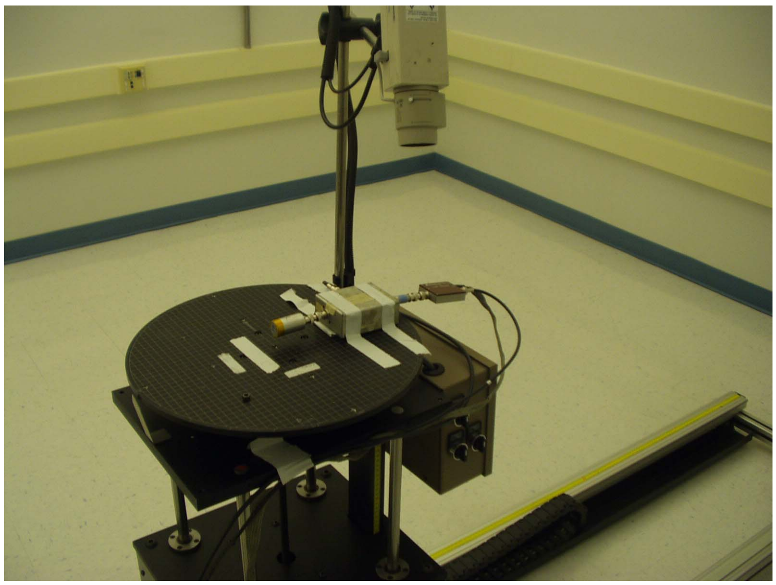

Figure 2. Silicon carbide detector on the test stand at the HPIL facility at INL.

For the tests at the HPIL facility, the detector was exposed to individual gamma and neutron sources covering a range of dose rates. At the Westinghouse facility, however, tests were conducted with the sources positioned separately and together to create mixed fields as illustrated in Figure 3. Throughout both the HPIL and Westinghouse tests the 28 mm^2 detector biased at -900 V was used in order to provide the maximum gamma-ray efficiency. All data signals were collected with the Acqiris DC282 digitizing at a rate of 8 GSamples/sec. The PSD algorithm developed and utilized in these tests first identifies pulses that are larger than a set threshold and wider than a given width in time. Three features of each pulse are measured: the amplitude, peak time, and the 10 to 90% rise-time of the peak. A rise-time error is also calculated based on the how well the signal matches a straight-line approximation of the 10 to 90% of peak amplitude section. This percent error is useful for rejecting less than ideally shaped pulses or noisy pulses.

Figure 4 illustrates the combined data containing the gamma-only cases from both HPIL and Westinghouse. In all cases the maximum value of the detector signal did not exceed 20 mV and over 99.9% fell below 18 mV. Measured risetimes generated by the gamma sources ranged from around 1 ns to over 5 ns. However, when this same processing is applied to the primarily neutron emitting sources (AmBe and ^{252}Cf) a much different result is obtained. The PSD algorithm indicates that the neutron signals have a broad spectrum of amplitudes which can be as high as 200 mV. Most striking, however is that unlike the gamma data which have a broad range of risetimes, the neutron data have a very well defined band of risetimes which is centered about 1.25 ns. Figure 5 illustrates the combined AmBe and ^{252}Cf spectrum which clearly defines this band. When both the gamma source data and neutron source data are plotted together the differentiation based on risetime is clear.

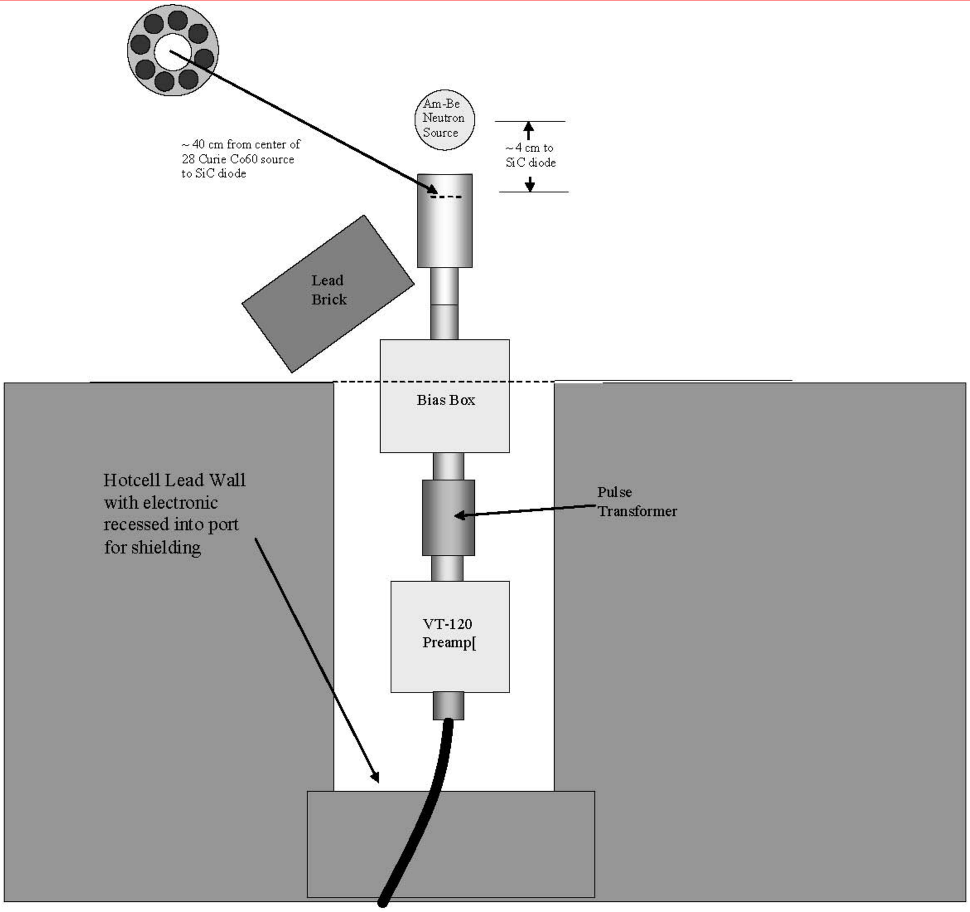

Figure 3. Plan view layout of the source and detector locations utilized in the Westinghouse experiments.

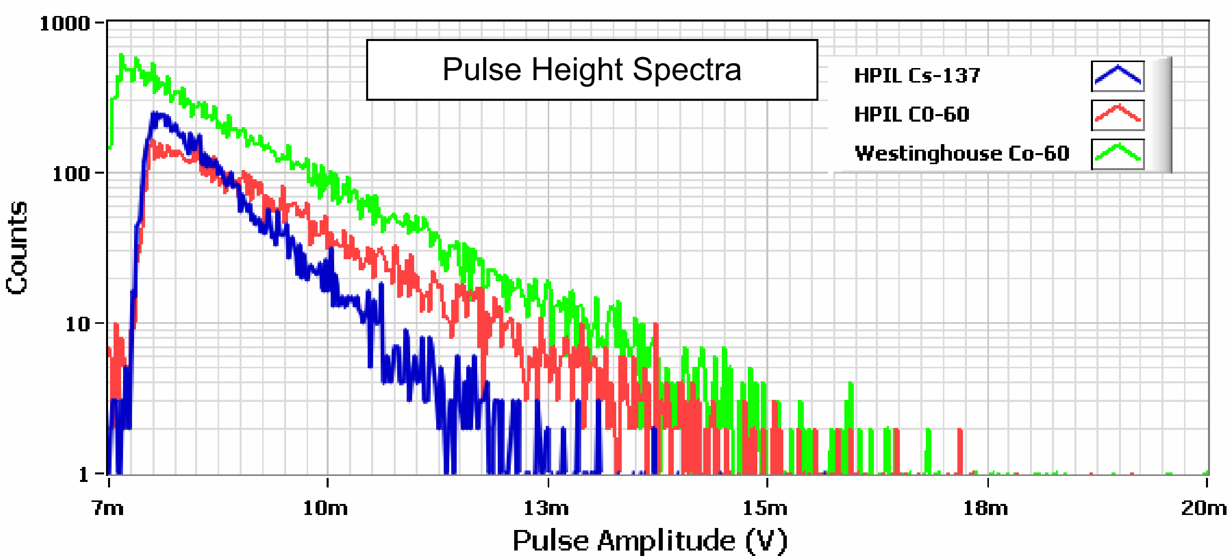

Figure 4. Gamma-only data processed with the PSD algorithm for the gamma-only cases from both the HPIL and Westinghouse tests.

This difference in risetimes between the neutron source data (AmBe, ^{252}Cf) and gamma source (^{137}Cs, ^{60}Co) data is presented in Figure 6. The wide distribution in the gamma source data in contrast to the narrow band from the neutron sources is apparent. Of the 15,338 total counts in the combined plot in Figure 5, 13,924 (90.8%) fall between the risetime values of one and 1.7 ns. When the 18 mV amplitude threshold is applied along with the risetime criteria, 63.8% of the signals fall within the "neutron" acceptance window. Obviously there are signals which fall outside of the window. While these may be attributed to poor statistics or noisy signals, they are very likely due to emitted gammas from the sources. In addition to the gammas produced by neutron induced reactions, both ^{252}Cf and AmBe emit gammas directly. In the case of ^{252}Cf there are, on average, 7 gammas emitted per fission. AmBe will emit a 4.4 MeV photon for nearly every neutron that is emitted.

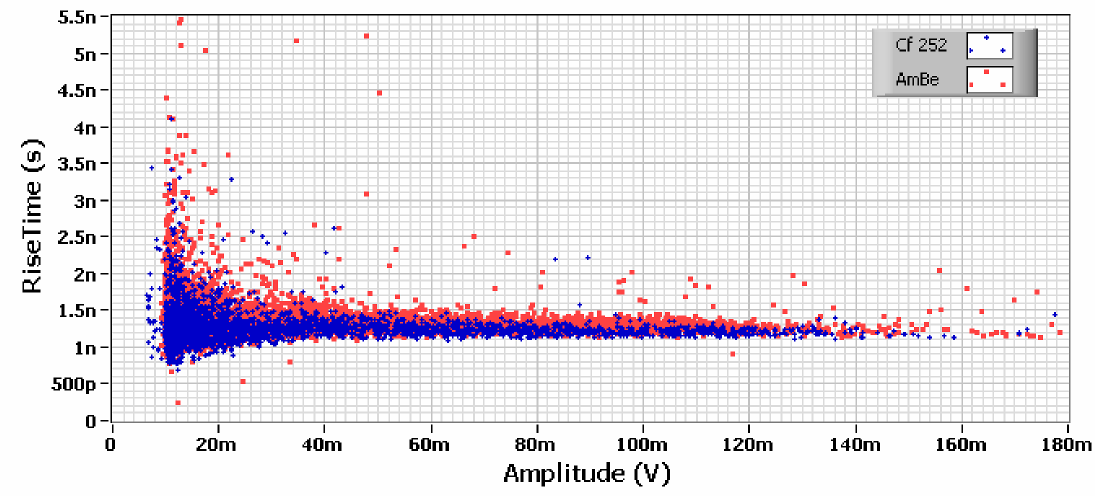

Figure 5. Combined neutron source data processed with the PSD algorithm.

The power of PSD can be further illustrated in the following example from the mixed field experiment at Westinghouse. For the geometric spacing illustrated in Figure 3, the SiC detector would have seen an integrated flux of 1.57×10^7 neutrons from the AmBe source and 4.2×10^{10} gammas from the ^{60}Co during the 25 minute collection time. Based on the intrinsic efficiency alone, the detector would be expected to register 7 neutrons for every 1000 gammas (0.7%). If the PSD algorithm is applied as illustrated in Figure 7, the ratio becomes 116 neutrons detected for every 1000 gammas (11.6%). This is an improvement of better than a factor of 16 over gamma suppression provided by detector efficiency.

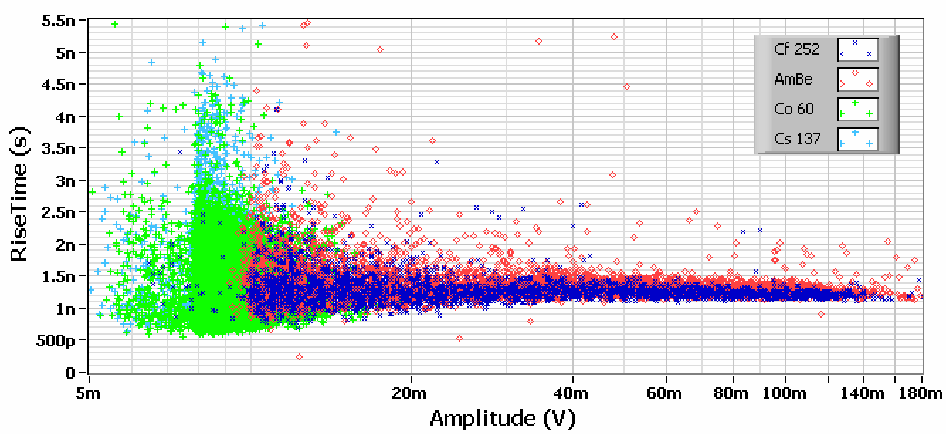

Figure 6. Combined gamma and neutron data processed with the PSD algorithm.

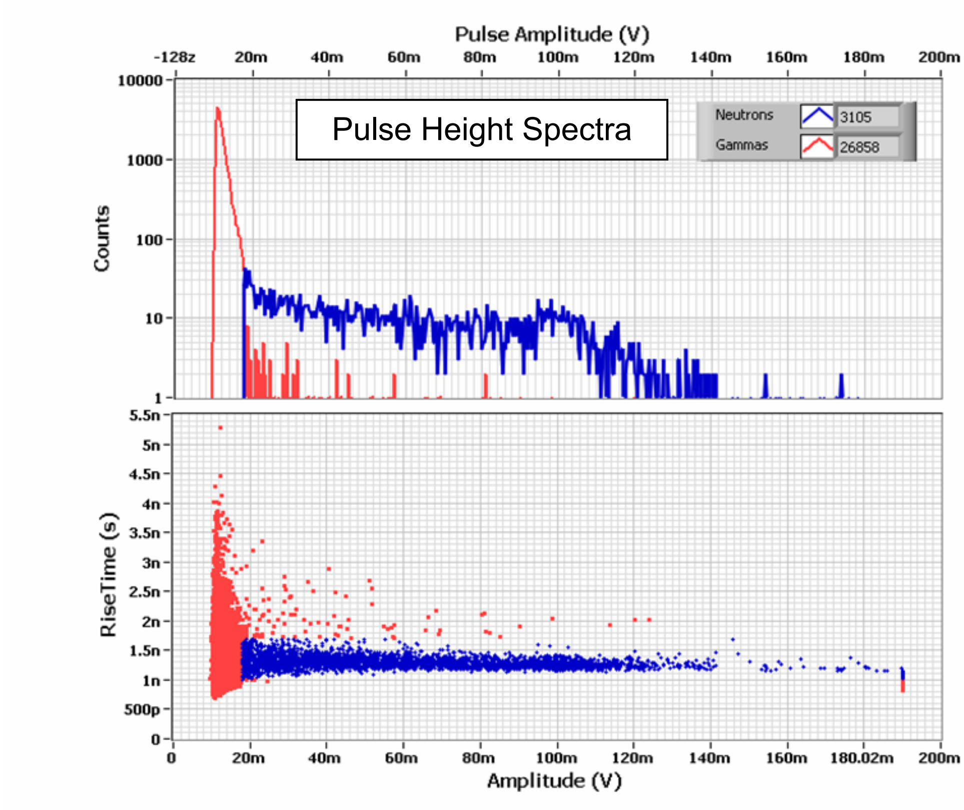

Figure 7. PSD applied to a mixed field radiation environment resulting in improved n:γ detection ratio.

4. CONCLUSIONS

PSD has been demonstrated to be a viable mechanism to differentiate between gamma and neutron produced signals in SiC detectors. PSD is possible in a SiC diode because the shape and timing of the signal produced is dependent largely on the type of radiation causing the interaction. Gamma radiation will interact primarily through Compton scattering with atomic electrons of the silicon, carbon, or nitrogen dopants in the materials. Recoil electrons are then emitted with ranges that are generally much larger than the thickness of the active layer. As these electrons pass through the active layer they generate ion-hole pairs which are collected and registered as signal. Photons greater than 1.022 MeV can also lead to pair production in the material, primarily the silicon, but this is typically 10-100 times less likely than Compton scattering for photons below 10 MeV. Because the ion-hole pairs generated through gamma interactions are dispersed throughout the active volume, the charge collection time is slightly greater than that caused by heavier charged particles. Neutrons, on the other hand, interact either through proton recoils generated in the polyethylene conversion layer placed on the upper edge of the diode or through (n,α) or (n,p) reactions directly in the silicon or carbon, if the neutron energy is sufficient. These heavy charged particles deposit their energy within a few tens of microns of the originating location. This results in a faster charge collection time when compared with gamma events. Exploitation of these differences in the risetime of the signal has been shown to separate gammas and neutrons in intense mixed fields which are indicative of active interrogation applications. Neutron signals were found to have broad amplitude spectra with risetimes falling within a narrow band centered around 1.25 ns. Gamma signals were found to have a much broader spectrum of risetimes and to have amplitudes of less than a few tens of mV.

5. ACKNOWLEDGEMENTS

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