Neutron Pileup Algorithms For Multiplicity Counters

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Abstract

The shortage of helium-3 (^3He) has created a need to identify alternative neutron detection options for a variety of nuclear nonproliferation applications. One application that may be affected by ^3He replacement technology is that of mass accountancy for safeguards, which utilizes coincidence and multiplicity counters to verify special nuclear material declarations. The use of neutron scintillation materials, such as LiF-ZnS sheets, as an alternative to ^3He proportional tubes in multiplicity counters requires novel techniques for Pulse Shape Discrimination to distinguish between neutrons and gamma rays. These techniques must work under high count rates, as the maximum momentary rate for incoming neutrons from multiplicity events can be quite large. We have created a fast and accurate neutron discrimination algorithm based on time window filtering and signature comparison that can operate quickly on data with high degrees of gamma ray and neutron pileup. This algorithm is evaluated for its capability to separate signals as the pileup rate increases, and the possibility for implementation on fast hardware (e.g., FPGA hardware) for real-time operation is explored.

Keywords: Multiplicity Counters; LiF/ZnS; ^3He Replacement; Pulse Shape Discrimination

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1.0 Introduction

Helium-3 (^3He) is used in a variety of neutron detection systems, including neutron multiplicity counters for safeguards applications. Multiplicity counters verify the declared mass of special nuclear materials by counting multiple neutrons arriving in a short time window as a result of spontaneous fission. However, due to the depletion of global ^3He reserves and forecasted limited production [1], alternative materials are being investigated as potential replacements.

A candidate technology for ^3He replacement in multiplicity counters is lithium fluoride (LiF) mixed with zinc sulfide (ZnS), which has been shown by prior work to outperform other alternatives based on the metrics of system efficiency and die-away time (characteristic lifetime of a neutron in the counter) [2]. This material has a much higher gamma ray sensitivity than ^3He , but the electronic pulses arising from gamma-ray energy deposition have a reasonably short decay time ($<1\text{ }\mu\text{s}$), and therefore can be discriminated from neutron pulses using Pulse Shape Discrimination (PSD) techniques. Several PSD techniques have been used for a variety of detection systems and applications, including the detection of neutrons against gamma-ray background [3]. In this paper we concentrate on the integration of the total measured charge over two different time periods and the examination of the ratio of these two measurements.

In this paper, we present measured data from a test LiF/ZnS detector, as well as a description of an algorithm for performing PSD under conditions of high signal pileup, such as would be expected during multiplicity measurements. Previous efforts applying PSD to highly piled-up gamma and neutron signatures found significant false neutron detection with high overall event rates, necessitating significant pileup rejection to achieve effective event type separation [4,5]. For event rates in the several hundred kilohertz to megahertz range, pileup will make the

traditional PSD approach of using the ratio of the total signal within short and long time windows difficult, as the windows may be occupied by multiple confounding signatures. To achieve high neutron counting efficiency at high total event rate requires a time-filtering technique able to discriminate between neutrons and gamma rays over a short time scale. An exploration of filtering techniques was undertaken to identify methods able to separate piled-up pulses from each other, while simultaneously distinguishing neutron and gamma ray responses.

2.0 Methods

A ^3He -based multiplicity instrument called the Epithermal Neutron Multiplicity Counter (ENMC) was used in previous work as the baseline for the performance requirements of alternative technologies for safeguards [6]. This detector was chosen due to its high neutron efficiency. Computer models of the ENMC were developed in the Monte Carlo N-Particle eXtended (MCNPX) [7] simulation environment, and used as the standard for comparison with alternative technologies. In particular, a ^6Li -based alternative detector material demonstrated promising simulation results [2]. The commercially available ^6Li technology used in this effort consisted of enriched lithium fluoride (^6LiF) powder mixed with silver-activated zinc sulfide (ZnS:Ag) powder (manufactured by Eljen Technology, Sweetwater, Texas). The particles of both materials are on the order of $10\text{ }\mu\text{m}$, in order to provide close contact with each other, and are held together by an organic binder. The neutrons are captured in the ^6Li , and a triton and alpha particle are emitted in the capture reaction. These charged particles interact in the surrounding material and deposit energy into the zinc sulfide scintillator. Zinc sulfide is a bright scintillator ($\sim 160,000$ photons per neutron [8]); however, it is not transparent to the scintillation light generated. Therefore, only thin sheets of $^6\text{LiF/ZnS}$ are useful, on the order of $500\text{ }\mu\text{m}$ or less. An optimized configuration modeled using this technology consisted of 14 trapezoidal

plates of 20 alternating layers of ${}^6\text{LiF}/\text{ZnS}$ and moderator/light guide arranged around a central cylinder.

To begin evaluating the performance of LiF/ZnS sheets as a replacement for ${}^3\text{He}$ in multiplicity counters, a test unit was constructed at PNNL. This unit employed four panels, each consisting of layered scintillating sheets with a plastic light-guide to transmit the scintillation light to photomultiplier tubes (Fig. 1).

Figure 1. Lithium fluoride/zinc sulfide Lab Demonstrator System. MCNP Model (left, top view) and Actual (single panel shown).

2.1 Digitizer System

To produce the data necessary to simulate pileup, neutron and gamma signatures were produced using the ${}^6\text{LiF}/\text{ZnS}(\text{Ag})$ demonstrator system, by exposure to a neutron (${}^{252}\text{Cf}$) source and a gamma ray (${}^{60}\text{Co}$) source. In each case these sources had low enough activity to avoid pileup and were used for testing purposes. A DGF Pixie-4 (manufactured by XIA LLC, Hayward, California) data acquisition system was used to digitize the pulses for post-experiment processing. The Pixie-4 digitizes the signals in a 14-bit Analog-Digital Converter (ADC) at a

rate of 75 MHz [2]. Data from each PMT (when data was collected simultaneously from two PMTs mounted on the same panel) was digitized and is displayed in Figure 2. Here, data from each PMT is summed together to produce an event. The data is summed based on trigger time, effectively adding the two similar signals to enhance statistics. In general, gamma rays interacting with the detector produce narrow peaks in the data set, while neutrons produce a much broader peak structure, allowing an easy determination of event type by eye.

Figure 2. Example gamma event (left) and neutron event (right), each PMT and in coincidence.

2.2 Data Production

In order to evaluate the effectiveness of these techniques in identifying neutron signatures in cases of significant pileup, synthetic data representing piled-up gamma and neutron events are produced by summing the data from individual measured events, which were then placed near one another in time (Fig. 3). In each case, “clean” gamma ray and neutron signature sets were generated by manually inspecting data and constructing sets of each type of signal well separated from other confounding signals. To obtain individual single gamma-ray and single neutron signatures, data from measurements of neutron and gamma sources were analyzed with a simple threshold. Then, the data around each peak found in this way were visually inspected to ensure

only single events were retained. A catalog of 360 gamma-ray signatures and 200 neutron signatures was constructed in this way to encompass the variation between individual events. Example neutron and gamma-ray events are shown in figure 2. This catalog was then sampled randomly and events were added together with the desired time offsets to create the desired synthetic data sets, with and without pileup, and with several ratios of neutron and gamma ray events.

Figure 3. Piled-up Neutron Signatures (simulated with Poisson-distributed arrival times).

In the case of well-separated events, neutron and gamma signatures can be discerned from one another by employing pulse shape discrimination techniques. However, real data from fission events will happen with very low time standoff and may lead to high pileup in the detector system. Traditional fixed PSD windows will include nearby events, ultimately leading to misidentification of events, as shown in Fig. 4. Here, data are simulated with varying degrees of pileup (enumerated as the average standoff time between events) and the exact event placement is random and Poisson-distributed, while the degree of total events that are neutrons is varied between 0 and 100%. When no real neutrons are present and pileup is high (i.e. the average

offset between events is low), secondary events overlap with the longer of the two PSD windows, leading to over-count. Likewise, when the overall neutron rate is high along with pileup, difficulties separating events and applying distinct triggers to each lead to undercounting.

Figure 4. Traditional PSD on Piled-up data. Dashed lines correspond to “ideal” neutron identification.

2.3 Pulse Shape Discrimination

These limitations require a new PSD methodology that must be adaptive to nearby events, capable of taking information from overlapping signatures, and must be fast enough to run in real time if possible. To meet these needs, an iterative, multi-stage regressive approach has been developed to separate signals under pileup. This event analysis begins with a development of the exemplar response function for neutron and gamma ray signals from the detector. Signatures for neutron and gamma ray signals are constructed by averaging examples of these events from actual data (Fig. 5).

Figure 5. Piled-up Neutron Signatures (Simulated with constant standoff).

To perform the signal analysis, an initial “conditioning stage” is applied to the data to isolate the individual peaks in the signal. First, a time window as short as possible (similar to the width of a gamma-ray peak) is passed over incoming signal data, with a simple threshold on peak height to describe event time and amplitude. Only peaks that are local maxima within this time window are accepted, to minimize the effect of noise in the signal and avoid adding spurious neutron detections. This has the effect of pile-up rejection for events more closely spaced than this window. These 2 parameters (peak height threshold and time window) affect the overall performance of the method, and were chosen to provide the highest neutron detection rate without significant false neutrons being detected. The time window for the new method presented in this paper was set to $0.68 \mu\text{sec}$ to correspond approximately to the width of a single gamma-ray peak. It was found that a shorter time window than this would lead to significant false neutron detection. Similarly, the threshold amplitude was set to around half the height of the smallest signature in the catalog, to ensure all well separated events were located.

For each event thus located, a broad surrounding time window is then used to group all events that may be piled-up together. These grouped events are then fit as an ensemble to each possible permutation of neutrons and gamma rays by comparing the signatures to the measured data, and

1 the most likely identification (i.e., neutron or gamma ray) for each event is made using a
2 regression approach (Fig. 6). In this example case, the two overlapping events are compared
3 with each possible permutation of neutron and gamma, and the lowest sum of square errors as
4 calculated between the signatures and measured data (here corresponding to a neutron plus
5 gamma ray, in that order) is kept as the most likely set of real events. This approach is much
6 faster than a “traditional” regression scheme, as the event location and height are not varied, but
7 set by the preceding algorithm step. For this reason, this technique can operate quickly in
8 comparison with a scheme that relies on simultaneously fitting all parameters. Using this
9 technique, data can be characterized for arbitrarily sized time buffers, for data with or without
10 pileup, and on an arbitrary number of piled-up events, from 1 (no pileup at all, a single true
11 pulse) to a number limited only by computational processing time.

Figure 6. Example Evaluation of Multiple Events by Signature Fitting. Vertical lines represent event locations. From top left: (γ, γ) , (γ, n) , (n, γ) , (n, n) .

3.0 Results and Discussion

Data sets with realistically-spaced data were created using these methods, and evaluated with a given average pileup to demonstrate the effect of realistic pileup on performance. In each case, a random standoff was picked to reproduce Poisson-distributed events; by definition, some events were closer, and some further away than average. Data with varying concentrations of neutrons and gamma rays were produced and tested to demonstrate the detection falloff for randomly spaced events, as shown in Figure 3.

Using this technique, traditional PSD is compared with the signature-fitting technique described above (Fig. 7). The traditional PSD is carried out using similar method, using an event finding and pileup rejection stage. Here, events are isolated with a time window of 2.6 μsec , slightly less than the width of a neutron peak, while the amplitude was the same as with the signature fitting technique. As with signature fitting, a significantly shorter pileup rejection window resulted in more false neutron detections at high real pileup, while a significantly longer one resulted in a lower overall performance.

In particular, the traditional PSD technique demonstrated high error at 10 μs event standoff and below, while the new method had better performance between 100 kHz and 1 MHz (10 μs to 1 μs average standoff). In addition, the effect from multiple gamma events adding together within PSD windows to produce a spurious neutron detection is greatly suppressed, as shown by the much lower response to a data set with no actual neutrons. While this effect could be reduced by increasing the pileup rejection window, this would also further suppress the overall neutron

detection rate. While some performance falloff is expected due to the presence of realistic and intermittent very-high-pileup events, the overall detection rate remains relatively high in a range close to 1 MHz.

Figure 7. Comparison of techniques with randomly distributed synthetic pileup data. Traditional PSD (Left) and Multi-stage analysis (Right).

4.0 Discussion and Conclusions

We have described a method for estimating neutron event rate and time in a manner much more robust to pileup than filter-based or traditional PSD techniques. This allows for limited falloff of efficiency into the MHz range. This may allow material verification by multiplicity counting using alternative detection materials. To be employed in multiplicity counting systems, these methods must be ported to fast (e.g., FPGA) hardware. Speedups to the computational methods are under consideration, and may include the following methods: Opportunistic single-event processing, where standard window-based PSD will be used only with single, well-separated events, and more complex methodology as needed. Coincidence-counting pre-filters are also being considered, in which events are only included if they that produce significant signal in both PMTs attached to a single scintillator element, to further reduce gamma ray signatures.

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6.0 References

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