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Characterizations of double pulsing in neutron multiplicity and coincidence counting systems

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ABSTRACT

Passive neutron coincidence/multiplicity counters are subject to non-ideal behavior, such as double pulsing and dead time. It has been shown in the past that double-pulsing exhibits a distinct signature in a Rossi-alpha distribution, which is not readily noticed using traditional Multiplicity Shift Register analysis. However, it has been assumed that the use of a pre-delay in shift register analysis removes any effects of double pulsing. In this work, we use high-fidelity simulations accompanied by experimental measurements to study the effects of double pulsing on multiplicity rates. By exploiting the information from the double pulsing signature peak observable in the Rossi-alpha distribution, the double pulsing fraction can be determined. Algebraic correction factors for the multiplicity rates in terms of the double pulsing fraction have been developed. We discuss the role of these corrections across a range of scenarios.

1. Introduction

Assay of special nuclear material (SNM) for international nuclear safeguards typically relies on nondestructive assay techniques such as neutron coincidence and multiplicity counting. This is most often done using ^{3}He-based detector systems and shift register analysis to extract and quantify neutron correlations [1,2]. These techniques suffer from detector and electronics effects such as dead time or can be affected by detector and electronics artifacts like double pulsing. The impact of these effects is often enhanced for high count rates bringing additional challenges to assay of samples with high neutron emission rates. Recent advancements in instrumentation and data acquisition systems (e.g. the feasibility of list mode—or event-by-event—data acquisition) make it possible to further evaluate and potentially mitigate these effects. Because SNM samples of sufficient grade and variability are often difficult or impossible to obtain, high-fidelity simulations frequently become a researcher's tool of choice for investigating the performance of these assay systems. Further, simulations are uniquely able to isolate and quantify the effects of dead time and double pulsing, since these effects can be individually added, removed or modified, although the validity of any simulated results still needs to be benchmarked against experimental data.

Recent results have shown that contrary to the commonly-held assumption that a pre-delay is effective in eliminating the effect of double pulsing in shift register-based time correlation analysis, double pulsing still affects the measured coincidence rates [3]. This research also showed that double-pulsing yields a distinctive signature in the Rossi-alpha distribution (RAD), giving an advantage to RAD analysis over a traditional multiplicity shift register analysis approach, which as routinely practiced does not yield any immediately obvious evidence of the presence of double-pulsing. A RAD is a histogram of time differences between a trigger pulse and every pulse that comes after it within the RAD gate time period. Each pulse in a pulse train acts as a trigger pulse. The information contained in this type of RAD is the singles rate, doubles rate, and die-away profile of the counter [4–6]. In traditional multiplicity shift register analysis, every pulse opens a coincidence gate after a short period of time (pre-delay), which is meant to avoid the most severe effects of dead time. The pulses within this gate are counted and recorded as a combination of real coincidences and accidental coincidences, populating a reals+accidentals histogram. After a long delay, a second gate called the accidental gate is opened and these correlations are recorded as purely accidental coincidences, populating the accidentals histogram. The moments of these histograms can then be used to find the higher multiplicity rates in addition to the singles and doubles.

While previous work [3] focused on the effect that double pulsing has on singles and doubles rates and noticed a signature of double pulsing in the RAD, current research characterizes the quantitative effects double pulsing has on both the RAD and the

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correlated rates, including higher order multiplicities not addressed in [3], so as to be able to recognize and correct for it. Additionally, in this paper the effects of the double pulsing fraction and its temporal distribution are explored, suggestions for correcting the double pulsing effects are made, and the double pulsing relationship with dead time is qualitatively discussed. This is initially done with simulations, where double pulsing can be explored without the contributions from dead time that affect real world measurements, but the general trends are then compared to experimental data.

2. High-fidelity neutron coincidence counter simulations

Because in experimental data the effects of non-ideal behavior like dead time and double pulsing can be inextricably combined, simulations can be used to disentangle their individual effects and explore a wider range of sources than may be experimentally available. Further, the specific dead time and double pulsing characteristics can be manipulated in a controlled manner. For this reason, simulations were used to probe the effects of double pulsing at a variety of double pulsing fractions, for a range of neutron source strengths, and with different double pulsing characteristics. The double pulsing fraction, r, is defined as the fraction of pulses that do not correspond to an actual neutron detection but are triggered by one. Unlike spurious noise, these pulses are temporally correlated to a pulse that does correspond to a genuine neutron detection.

As the design of ^{3}He counters can have an effect on the intensity and magnitude of imperfections such as double pulsing, the starting point of these simulations is as accurate and detailed a description of an actual counter as possible. Neutron coincidence and multiplicity counters are typically a composite of many ^{3}He tubes, with several tubes electronically bundled to the same preamplifier. Note that preamplifiers refer here to a signal processing unit composed of signal shaping and identification and logical pulse generation. Noise and dead time can be introduced in principle anywhere from the initial preamplifiers through to the final electronic OR where the outputs from individual preamplifiers are combined to typically one output for readout. To simulate double pulsing and dead time, the neutron-capture location (i.e. in which ^{3}He tube the capture occurred) along with the time of a neutron detection is tracked, so it is possible to add these electronic imperfections to the simulations on a preamplifier level.

The Monte Carlo transport code MCNPX [7] was used to model the neutron counters, fission sources, and all neutron interactions and transport. Realistic MCNP models have been made for a representative sample of the standard multiplicity and coincidence counters such as the Active Well Coincidence Counter (AWCC) [8], the Epithermal Neutron Multiplicity Counter (ENMC) with and without the Inventory Sample (INVS) insert [9,10], the High-Level Neutron Coincidence Counter (HLNCC) [11], and the Plutonium Scrap Multiplicity Counter (PSMC) [12]. The AWCC was chosen as a well-characterized representative from this group. It was assumed that when double pulsing manifests on all the preamplifiers equally, the effects on the rates should be similar, if not the same, for all counters. This would not be the case if an individual preamplifier double pulsed at a different rate from the other preamplifiers, however.

The capture-type Particle Track Output Card (PTRAC) output file from the MCNP simulation was used to create a pulse train (i.e. a sequence of neutron capture times) using FastTrain, a C#-based, Los Alamos National Laboratory (LANL) developed code with a graphical user interface [13,14]. The PTRAC file includes information on every neutron capture event of interest (e.g. a neutron captured within a ^{3}He proportional detector tube), such as final location and time of neutron capture. From the PTRAC file, FastTrain extracts the location of neutron capture in the form of an MCNPX cell number corresponding to an individual ^{3}He proportional detector tube along with time information for each neutron capture and generates list mode type data, with a separate output file for capture times and cell numbers respectively. The neutron capture times in a PTRAC file are times with respect to a spontaneous fission event within the assayed sample. With a user-defined spontaneous fission frequency, absolute times for neutron captures can be established and recorded with FastTrain.

The analysis code FastTap [15], a LANL-developed software expanded from VBTap [16], can extract standard shift register multiplicity rates (singles (S), doubles (D), triples (T), quads (Q), and pents (P)) and create RADs and time interval distributions. FastTap can read both simulated and experimental list mode data. For the simulated data, FastTap has additional features that allow for improving the fidelity of the synthetic data. FastTap is able to implement both dead time of various levels of sophistication and double pulsing with specific characteristics on the list mode data before analyzing. This feature allows the user to analyze the same pulse train with and without dead time and double pulsing and/or modify the parameters of both effects.

In the most current version of FastTap (FastTapX 1.3) the double pulsing is being added at the preamplifier level with all preamplifiers double pulsing with the same fraction. This considers the generally accepted origin of double pulsing being on the level of the preamplifiers (see Section 3). The option for each preamplifier double pulsing with different fractions may be added in the future. In the context of this research, all simulations were carried out without dead time. Simulations combining double pulsing and dead time is a topic of future research.

For this study, the AWCC was selected as it represents a standard neutron coincidence counter commonly used by safeguard inspectors worldwide. Originally developed at LANL, it is commercially available from ANTECH and Canberra [17,18]. The AWCC has 42 ^{3}He proportional counters with groups of 7 detectors connected to a single signal processing preamplifier, for a total of 6 preamplifiers. The TTL logic pulse outputs of these 6 preamplifiers is then connected to a master OR, a logic gate that outputs a single pulse train of digital timestamps corresponding to individual neutron detections.

Initially, we use a random neutron source created with a random number generator to observe the effect of double pulsing. Then, we show the effects of double pulsing in the context of nonproliferation and safeguards measurements by simulating the AWCC with a 4-kg sphere of low-grade Pu metal (90% ^{239}Pu and 10% ^{240}Pu). Finally, we explore the effects of double pulsing with simulated assay of several ^{252}Cf sources of various strengths using the AWCC. This is to simplify the problem and show the effects of double pulsing on a correlated neutron source without the additional level of complexity due to the effects of multiplication. The activity of the ^{252}Cf source in simulations was varied using FastTrain.

To study the effects of double pulsing, pulse trains with double pulsing were simulated such that a second pulse was inserted into the pulse train with a user-defined probability in a randomized Gaussian distribution with respect to the triggering pulse. Using this method, the modified pulse trains can be analyzed with either shift-register type analysis or a RAD.

3. Origins and recent studies of double pulsing

Double pulsing is thought to have two primary sources. In the first case, it arises from the electron-ion collection within the ^{3}He tube. A thermal neutron detection is essentially a detection of the