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Extraction of correlated count rates using various gate generation techniques: Part I theory

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ABSTRACT

This paper presents an overview of different gate generation techniques that can be used to extract correlated counting rates from neutron pulse trains in the context of Passive Neutron Multiplicity Counting (PNMC). PNMC based on shift register pulse train time autocorrelation analyzers is an important Non-Destructive Assay (NDA) method used in the quantification of plutonium and other spontaneously fissile materials across the nuclear fuel cycle. Traditionally PNMC employs signal-triggered gate generation followed by a random gate, separated from the trigger pulse by a long delay, to extract the totals rate (gross or singles), the pairs (coincidences or doubles) rate, and the triplets (or triples) rate of correlated neutron pulse trains. In this paper we provide expressions for singles, doubles and triples rates using the information available in both, the random and signal-triggered gates (traditional shift register analysis), in the randomly triggered gates only, and introduce a third approach to extract the correlated rates using signal-triggered gates only. In addition, we expand the formalism for randomly triggered gate generation to include Fast Accidental Sampling (FAS) and consecutive gate generation.

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Introduction

Non-Destructive Assay (NDA) neutron techniques traditionally utilize time correlations between detected neutrons to provide quantitative assay of spontaneously fissile material. The correlations are extracted from a neutron pulse train detected in a coincidence/multiplicity counter. In addition to total count rate (singles, *S*) coincidence counting extracts pairs of correlated neutrons (doubles, *D*). In case of high-efficiency (multiplicity) counters higher order correlations such as triples (*T*) (or even higher orders, such as quadruples or pentuples) can be extracted. The analysis technique typically employs multiplicity shift register circuitry [1] to generate signal-triggered coincidence gates and tally the multiplicity distribution from which the factorial moments that define *D*, *T* and the higher order rates can be computed. The random (chance or pile-up) contribution to the correlated signal is evaluated using a long delay following the signal-trigger to generate a corresponding series of random coincidence gates with respect to the trigger—meaning that the events observed in the late gate are not correlated with the trigger.

Alternatively the pulse train can be sampled using random gate generation only, that is, with no signal-triggered pulse required. The random gate generation can also be implemented using a series of gates generated at high frequency as is the case in Fast Accidental Sampling (FAS) in modern Multiplicity Shift Registers (MSR) [2]. Similarly, a sequence of consecutive, non-overlapping gates can be used to quantify the degree of correlation on the pulse train. In addition, random gate generation following a long delay after the signal-triggered pulse, as implemented in traditional MSR, can be also utilized to perform analysis on random gates only, since although the events are not correlated to the trigger, the segments of pulse train analyzed still contain correlation.

The traditional MSR-based analysis combines information from signal-triggered as well as randomly triggered gates in order to extract the correlated rates [1–3]. Here we shall refer to this approach as the *MIXED* technique. The formalism of randomly triggered counting utilizes solely the information available in the random gates to extract the corresponding multiplicity distributions and *S*, *D*, *T* rates [3]. This approach shall be referred to as the Random Triggered Inspection (*RTI*) technique in this paper. The basis of *RTI* technique was derived in [3] but assuming a sequence of consecutive, non-overlapping gates. In MSR analysis the coincidence gates overlap because they are opened by the in-coming events. This approach will therefore be discussed in the context of MSR-based analysis and also extended to the case of random sampling, where a fixed clock frequency is used (FAS and consecutive gate generation). In addition, a third gating technique

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will be introduced, which solely utilizes information available in signal-triggered gates to extract the corresponding *S*, *D*, *T* rates. This technique will be referred to as Signal Triggered Inspection (*STI*).

Pulse train analysis techniques

In this section the formalism to manipulate the multiplicity histograms to extract the correlated rates will be explained in more detail. While the singles rate has an intuitive meaning as the mean detected neutron event rate, the doubles rate and the rates of the higher observed reduced factorial moments are creations of the shift register autocorrelation technique used to extract and reduce the correlated information that is present on the pulse train. They are not fundamental quantities in themselves but rather convenient intermediate quantities which can be related to physical quantities such as spontaneous fission rate, leakage (or total) multiplication, detection efficiency and the ratio of the random neutron contribution from (α,n) reactions to neutrons from spontaneous fissions, (SF,n). The question of how these higher order correlated rates are extracted from the pulse stream for each of the inspection techniques is discussed below.

Signal-triggered gate generation

This technique is traditionally implemented in multiplicity shift register hardware, where a series of flip flop circuits is used to count individual incoming pulses and build multiplicity distributions [1]. In the signal-triggered gate method each incoming neutron pulse opens a gate of predefined width (T_g) following a short pre-delay time T_p. The purpose of the predelay is to allow the detection efficiency to return to its normal value following the perturbation to the detector caused by the detection of the triggering event. The predelay usually corresponds to a small fraction ($<10\%$) of T_g, typically below 2 μs for modern multiplicity counters based on moderated ^{3}He-filled proportional counters. The signal-triggered gate is used to count real+accidental coincidences ($R+A$) and build the coincident neutron multiplicity distribution, $N(i)$, which will be referred to in this paper as the Signal Triggered Inspection (*STI*) multiplicity histogram. In order to estimate the contribution of accidental coincidences, a second gate (accidentals gate or *A*-gate) is opened after a long time T_L following the trigger. The time must be sufficiently long to ensure that any correlation between the trigger pulses and counts in the *A*-gate is lost. The *A*-gate is used to build the accidental coincidence multiplicity distribution, $B(i)$. Using information contained in $N(i)$ and $B(i)$ multiplicity distributions, the true correlated rates can be determined as will be shown below.

Randomly triggered gate generation

The accidentals (delayed or *A*-) gate that is generated in the technique described above can be considered as a randomly triggered gate. Because the *A*-gate is not opened until a long (compared to the mean neutron lifetime in the system) time, T_L, after both the trigger event and the ($R+A$)-gate are closed, any correlations with the triggering event have effectively vanished. The opening of the *A*-gate therefore forms a random sample of the pulse train and for this reason is referred to as the Random Triggered Inspection (*RTI*) multiplicity histogram. It is important to understand that the *RTI histogram* is (statistically) equivalent in terms of expectation value, apart from for the number of gate openings and some overlap, to the histogram that would result from a periodic inspection of a gate of equal duration because the pulse train is random in time. In the MSR context, because every pulse opens the corresponding *A*-gate, the pulse train is oversampled. However, by sub-dividing the counting time into a number of shorter repeat cycles it is possible to evaluate mean values of quantities of interest along with estimates of the precision including any correlations, directly from the scatter in the cycle data. Thus, the oversampling ensures that all neutrons contribute to the histogram and is not in itself a hindrance to application nor to the quantification of the precision. The *RTI histogram* can be thought of as the background for the *STI histogram* (for doubles counting at least) although it still contains correlated information since the events that fall within it may be in close proximity owing to them coming from the same initial burst created in the measurement item. Formally therefore, and as we shall see numerically later, correlated signatures may be obtained from analysis of either the $N(i)$ histogram, the $B(i)$ histogram of from a combination of the two (as in the case of the MIXED approach).

Since we are currently focused on conventional MSR-based analysis, we will assume in the following that the number of ($R+A$)- and *A*-gates openned is equal. This is the case, since every detected neutron in the pulse train opens both, the ($R+A$)-gate as well as *A*-gate. Later in this paper the modification of the expressions for correlated rates due to different sampling techniques, such as FAS or consecutive gate generation, will be discussed. The benefit of the FAS scheme is most evident at low to modest counting rates and comes about by virtue of the fact that by massively oversampling the pulse train, using a periodic inspection rate (usually far) greater than the counting rate, effectively no scrap of information is lost. In other words why open just a single delayed *A*-gate per incident event when equally good segments of the pulse train, both earlier and later in time, would be statistically equivalent. The FAS recognizes this and draws on the whole pulse train throughout the entire data acquisition period to estimate the $B(i)$ histogram in order to achieve better statistical precision.

Working with the multiplicity histograms

Assuming the standard MSR analysis, using ($R+A$)- and *A*-gates, the basic relations for the correlated rates (multiplets) in terms of the item and detector parameters and how they may also be extracted from the histogram data may be derived from a careful study of the detailed mathematical development given by Hage and Cifarelli [3] and is rooted in earlier reactor noise theory [4,5]. We shall limit our discussion only to the usual case of singles, doubles and triples, since experimentally these are often the only three quantities that can be routinely determined for safeguards items and instruments with viable precision in reasonable assay times on practical assay items. Expressions for quadruples (Quads) and pentuples (Pents) may be found elsewhere [6]. A detailed formalism was developed in [3], where rates R_μ/T_M ($\mu=1$ to 3 and T_M=assay time) were derived that represent the true multiplet rates ($\mu=1$ to 3 correspond to singlets, doublets and triplets, respectively) corrected for any loss of pulses due to finite duration of the coincidence gate T_g. Note that quantities R_μ in [3] represent all of the counts over the entire measurement interval. In the context of MSR-based analysis, the singles, doubles and triples represent the count rates per second, based on pulses that fall within the finite coincidence gate window T_g and differ from these 'true' multiplet rates by an *STI* Gate Utilization Factor (GUF) [7,8]. The *STI* Gate Utilization Factor, f_μ ($f_1\equiv1$, f_2 is the doubles GUF, f_3 is the triples GUF etc.) corrects for the fact that not all the detected pulses were counted within the finite coincidence gate window T_g. Thus, in the terminology of [3] the *S*, *D*, *T* rates correspond to the multiplet rates R_μ/T_M,