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The optimum choice of gate width for neutron coincidence counting

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ABSTRACT

In the measurement field of international nuclear safeguards, passive neutron coincidence counting is used to quantify the spontaneous fission rate of certain special nuclear materials. The shift register autocorrelation analysis method is the most commonly used approach. However, the Feynman-Y technique, which is more commonly applied in reactor noise analysis, provides an alternative means to extract the correlation information from a pulse train. In this work we consider how to select the optimum gate width for each of these two time-correlation analysis techniques. The optimum is considered to be that which gives the lowest fractional precision on the net doublets rate. Our theoretical approach is approximate but is instructional in terms of revealing the key functional dependence. We show that in both cases the same performance figure of merit applies so that common design criteria apply to the neutron detector head. Our prediction is that near optimal results, suitable for most practical applications, can be obtained from both techniques using a common gate width setting. The estimated precision is also comparable in the two cases. The theoretical expressions are tested experimentally using ^{252}Cf spontaneous fission sources measured in two thermal well counters representative of the type in common use by international inspectorates. Fast accidental sampling was the favored method of acquiring the Feynman-Y data. Our experimental study confirmed the basic functional dependences predicted although experimental results when available are preferred. With an appropriate gate setting Feynman-Y analysis provides an alternative to shift register analysis for safeguards applications which opening up new avenues of data collection and data reduction to explore.

1. Introduction

Ensslin [1] provides an approximate plausibility argument, which has been shown to hold reasonably well in practice [2,3], that closely predicts the optimum gate width for use in shift register based coincidence counting. When the accidentals (or chance) coincidence rate far exceeds the real (or genuine) coincidence rate the gate width that returns the lowest relative standard deviation on the net real rate is predicted to be about 1.26 times the nominal 1/e neutron dieaway time of the detector system.

In this work we review Ensslin's derivation and adopt the same general reasoning to answer the question of what the optimum gate width is when Feynman-Y analysis [4] is being used to extract the correlation information from the pulse train rather than shift register logic. We do not expect the estimate to be completely accurate, because the pulse train from fission sources, by definition, is correlated and our theory does not account fully for this, but we do expect it to reveal the key functional dependences according to the current traditional understanding.

Traditionally multiplicity shift register (MSR) analysis records a multiplicity histogram to extract higher order moments (such as triplets) from the measurement multiplicity distribution. In recording the data, the MSR technique uses a single value of coincidence gate width that is chosen based on system characterization measurements. This is because traditional hardware devices usually only support a single gate width setting, although in future designs this limitation could well be lifted. In practice using a single gate width has been acceptable, even for general purpose applications, because the optimum setting, judged on the basis of minimizing the relative standard deviation on the net reals (coincidence or doubles) rate, for a given item lies at the bottom of a broad minimum provided the accidentals rate is dominant. In other words the exact choice of gate width under these conditions is usually not critical in the context of other sources of measurement uncertainty. Furthermore, for the small-mass items of safeguards interest, far from criticality, the neutron dieaway profile is utterly dominated by the characteristics of the neutron detector, not the assay item, and so the position of the minimum is not strongly dependent on the item either. For the assay of plutonium scrap and

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waste the situation is a little different in that the dieaway profile can be influenced by the matrix material and it may be prudent to use a wider gate (perhaps twice the dieaway time) to reduce any sensitivity to this effect. But in this case the usual analysis which assumes that the neutron detection efficiency is known and fixed is no longer valid either. To resolve this dependence a small ^{252}Cf source is introduced near the container and the matrix perturbation is determined directly. This so called add-a-source (AAS) or matrix-interrogation-source (MIS) approach therefore compensates for the change in the value of both the efficiency and the gate utilization factor (the fraction of correlated events on the pulse train that fall within the finite duration of the coincidence gate). Since the value of the gate width stays within the broad minimum the impact of not precisely choosing the optimal gate width is small. The exception to this shallow optimum rule of thumb is when assaying in the low-mass, low rate, regime, particularly close to the minimum detection limit, with chemically clean (low (α,n)-to-spontaneous fission neutron ratio) materials (as opposed to plutonium-bearing materials which may have low mass but high contribution of (α,n) neutrons). In this extreme the accidentals rate becomes negligible and no longer strongly influence the precision on the net correlated rate calculated and so to achieve the 'best' counting statistics in reals it becomes more important to obtain the highest possible signal. In this counting regime, instead of a gate width of about 1.26 times the dieaway time (as detailed below) a value of 2 or 2.5 times the dieaway time might be used instead so as to essentially integrate over the region of correlation in the 1-dimensional Rossi-α distribution. This choice then comes with the added benefit that variations in the gate utilization factor introduced by the matrix are also lessened (as was discussed for waste and scrap).

The optimum value of the predelay, T_p, is simply the minimum value necessary for the system to return to quiescent conditions following a detected event so that the accidentals subtraction might be made with negligible bias. The predelay is usually many times larger than the effective system dead time although it may be comparable to the maximum dead time of an individual counting channel. The predelay allows any baseline shift, which affects the trigger probability (efficiency) of small amplitude signals to dissipate. The predelay may be reduced by careful hardware design. But for a given system the predelay setting is not amenable to the statistical optimization in the way that the coincidence gate width is. Consequently we shall not discuss the choice of predelay further.

2. Optimum gate width selection – shift register (MSR) analysis

In the conventional multiplicity shift register (MSR) approach to neutron coincidence counting [1] every neutron event (signal) recorded on the pulse train triggers the inspection of a coincidence gate of width T_g after a short predelay, of duration T_p. The accumulated number of counts in the gate represents the number of pairs in coincidence with the triggering event. The count in the gate includes both genuine (or real) coincidences together with accidental (or chance) coincidences. For this reason this gate is called the 'reals plus accidentals' gate $(R+A)$. To evaluate the accidental coincidence contribution, another gate is opened a long time, T_L, after the $(R+A)$-gate is closed. The accumulated value of the number of counts in this gate gives the average number of accidental coincidences provided the long delay T_L is many times longer than the effective 1/e dieaway time, τ. Any genuine time correlation to the triggering event will then have dissipated after T_L has elapsed. It is because of this that the late gate is called the accidentals or A-gate. If the total (gross or singles) counting rate is denoted by S, then, on average, the A-gate will be opened S times every second and the average number of counts within each gate will be given by the product of the total event rate and the duration of the gate, ST_g. Thus under steady conditions the accidentals rate is expected to be given by $A=S^2T_g$.

To extract the genuine coincident rate, the information from $(R+A)$-gate and A-gate is combined in the traditional MSR analysis. Working in terms of count like quantities (as opposed to rates) and treating the correlated signal as if it were the result of a matched pair of independent Poisson variates we have for the net reals rate and the associated standard deviation:

$$R=\frac{1}{t}[(R+A)t-At]\pm\frac{1}{t}\sqrt{[(R+A)+A]t} \tag{1}$$

We emphasize that R and A are rates, so that Rt and $(R+A)t$ are counts, and we have made the assumption that the variance on the number of counts for a counting experiment is equal to the number of counts.

The reciprocal relative standard deviation in the limit $A\gg R$ then becomes:

$$\frac{R}{\sigma_R}\sim\frac{R_2f_2}{\sqrt{2tA}}\sim\frac{\sqrt{t}}{\sqrt{2}}\frac{1}{\sqrt{\tau}}\frac{R_2}{S}\frac{f_2}{\sqrt{T_g/\tau}} \tag{2}$$

where R_2 is the second factorial moment rate, sometimes called the doublet or second order multiplet rate, with the meaning that it is the net reals rate for the item with perfect gating. The factor f_2 is the gate utilization factor (GUF) [5] which accounts for the fact that not all coincidences present on the pulse train are counted because finite values of T_p and T_g are being used and some correlated events fall outside the gate. Perfect gating means the limiting result as T_p approaches zero and T_g becomes infinitely large compared to the lifetime of neutrons in the system for a detector free of instrumental artifacts (that is the reasons why we need a finite predelay are absent).

For a given item one could plot the (R/σ_R)-ratio as a function of T_g to find the value that gives the maximum. But here we want generic guidance based on theory rather detailed item specific information which will depend on the exact rates and temporal character of the system. For a detection system with a pure single exponential dieaway profile we have, upon substituting the theoretical expression for the GUF, f_2, and the calculated result for the accidentals rate $A=S^2T_g$:

$$\frac{R}{\sigma_R}\sim\frac{e^{-T_p/\tau}}{\sqrt{2}}\sqrt{t}\left(\frac{1}{\sqrt{\tau}}\frac{R_2}{S}\right)\frac{(1-e^{-T_g/\tau})}{\sqrt{T_g/\tau}} \tag{3}$$

The maximization problem therefore reduces to finding the turning point of the function:

$$\frac{(1-e^{-T_g/\tau})}{\sqrt{T_g/\tau}}=\frac{(1-e^{-z})}{\sqrt{z}}=y(z) \tag{4}$$

where $z=T_g/\tau$. In the limit $z\to 0$ we find $y(z)\to\sqrt{z}\to 0$ while in the limit $z\to\infty$ we find $y(z)\to 1/\sqrt{z}\to 0$ and the two extremes are connected by a simple continuous curve possessing a single maximum. Numerical evaluation gives the position of the maximum as $z=T_g/\tau\sim 1.2564$ [see Note to analytical discussion], and the value of $y(z)$ at the peak ~ 0.6382. This is the justification for why the 'best' choice of gate width quoted earlier takes on the value it does in terms of the 1/e dieaway time for an ideal detector with a pure exponential dieaway profile. We note that it has been shown that this simple result is *not* strongly perturbed by non-Poisson behavior or dead time losses in real systems [2,3]. Because the extension to the theory to account for correlations does not alter main functional dependences we have elected to use the simpler treatment here which is also by far the most commonly encountered form.

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