List-mode Enabled In-situ Analysis of Optimized Gate Widths for Neutron Based Nondestructive Assay Measurements to Maximize Throughput for Nuclear Material Accountancy

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Abstract

List mode enables the high-resolution acquisition of data from neutron based nondestructive measurements of nuclear material for control and accounting. The data is stored with complete fidelity in the spatial and temporal dimensions which allows iterative and sophisticated analysis techniques. A series of instruments, data acquisition electronics, software, and analysis are being developed to exploit the additional, complex information contained in list mode data. This work describes a list-mode enabled analysis technique to optimize a neutron instrument's gate width setting by iteratively re-analyzing the neutron data while varying the parameter until convergence on a minimum measurement uncertainty is achieved. This analysis technique will significantly improve measurement throughput and statistical precision for almost every neutron coincidence or multiplicity measurement performed in plutonium and uranium nuclear facilities around the world. While the technique is complex, it can be implemented in software and automatically performed with no burden on the end user.

The physics motivation relates to the fixed gate width commonly used in neutron coincidence and multiplicity counting. The gate width affects the fraction of real coincidences which are counted. Accidental coincidences contribute to statistical uncertainty and are, unavoidably, also counted. The amount of real and accidental coincidences contained in the gate both affect the measurement's statistical uncertainty, which informs real-world measurement times implemented by equipment operators. Fixed gate widths are used in almost all applications. However, the optimal gate width depends on the accidentals rate, which can vary by a factor of 2,000, and the reals rate. List mode data collection allows the re-analysis of the measurement to identify the gate width that provides the smallest statistical uncertainty. The analysis can be performed for every measurement, so the increased performance is achieved even if the item stream results in a mix of low and high accidental coincidence rates. This capability may allow reduced measurement times for almost every coincidence or multiplicity counting application worldwide.

Introduction

Traditional neutron coincidence and multiplicity electronics provide temporally correlated pulse rates (I.e. doubles and triples) [1, 2]. The development of new instruments, data acquisition electronics, and software, has resulted in the ability to easily collect time-stamped neutron pulse-trains, known as list-mode data [3]. List-mode data provides access to information that is not available with traditional shift-registers. For example, the same pulse train can be analyzed multiple times using different settings, which enables efficient experimental optimization of data collection parameters. This differs from the standard procedure for coincidence and multiplicity counting, which requires that several analysis parameters are set during the measurement to collect the singles, doubles, and triples rates. Two of these parameters, the dieaway time and the gate width, are typically established for a particular counter and then applied to all measurement configurations. The values that are selected for the predelay are based on the counter electronics, and the gate width settings are typically set based on two factors. The first is the rule of thumb that the gate width should be 1.256x the dieaway time as determined in [1]. The second is that, due to historical characteristics, the 1.256x value is rounded to some multiple of 2^x, typically 128 for waste counters, 64 for coincidence counters, and 24 to 64 for multiplicity counters.

The gate width that is utilized in multiplicity and coincidence counting analysis determines the window of time in which the pulse train is examined for temporally correlated neutrons following a trigger event. The gate width also determines the window of time that is used to calculate accidentally correlated pulses. Thus, the larger the gate width the higher the probability that all correlated events associated with the trigger pulse will be counted (which increases efficiency); however, this will also increase the accidental coincidence rate. This can be illustrated by examining the Rossi-Alpha distribution and the coincidences that are captured in the gates, shown for two examples, one for a low (α,n) source and one for a high (α,n) source, in Figure 1. As can be seen, if time 0 is the time of detection of a first neutron from fission, and the time of detection of subsequent neutrons is plotted, there will be real (R) coincidences from the same fission close in time and accidental (A) coincidences both close and far away in time. The real coincidences can be separated from accidental coincidences by subtracting an A gate from an R+A gate. In these two example Rossi-Alphas, the real correlated events (reals) are constant, and the accidental rate changes. Collecting more reals reduces the uncertainty of the (R+A)-A calculation, while collecting more accidentals results in increased uncertainty. Therefore, the gate width must be optimized for both efficiency and uncertainty. The collection of additional reals in a larger gate may be worth the additional accidentals for a low (α,n) sample, but not for a high (α,n) sample.

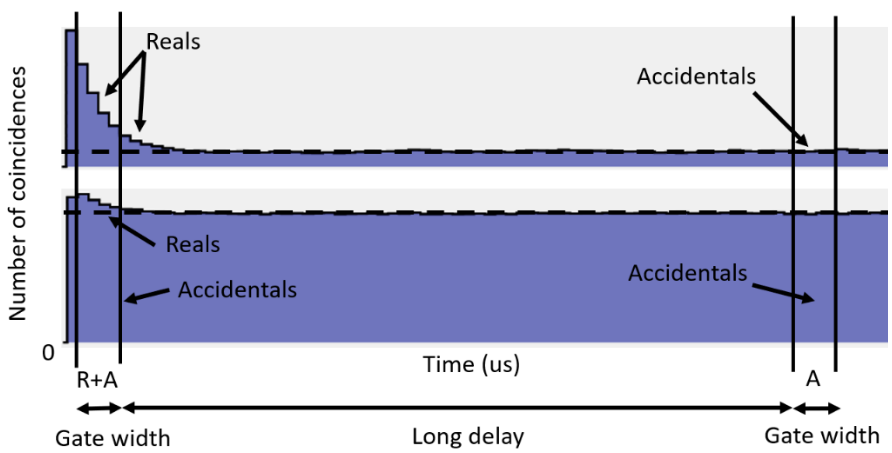

Figure 1. Rossi-alpha distribution for a low (α,n) source (top) and a high (α,n) source (bottom). The reals + accidentals and accidentals gate structure is shown. The figure was made with the Rossi Alpha View software [4].

The 1.256 value was determined analytically/numerically in [1] and further detailed in [5] and other references. It is based on the minimization of the relative standard deviation of the reals (rsd(R)) from the R+A and A gates. The calculation makes a key assumption, which is that A >> R, meaning the sample has high count rates from (α,n) or mass (kgs of Pu). Therefore, the typical gate widths used in nearly all coincidence and multiplicity counting applications are optimized for high (α,n) or large samples, while **many measurements are suffering from non-optimal gate width selection** because they are low (α,n) oxide and/or low mass samples. As we will show, the 1.256 value results in gate widths that are too short for typical samples. Shorter gate widths result in unnecessarily lower doubles and triples efficiency and the statistical uncertainty of the measurement could be reduced with better gate width optimization.

As was noted, list-mode enables the reals and accidentals to be determined for different analysis parameters. This allows these parameters to be optimized for different measurement configurations (e.g., low vs. high alpha, defined in Eq. 1). This study has specifically considered the effect of gate width on doubles and triples rates, and their associated uncertainty, as a function of sample alpha. Data was collected with several different samples, and the neutron pulse train was then reanalyzed using a series of gate widths. Additionally, the uncertainty associated with these values for each gate width was calculated; this analysis enabled a comprehensive comparison of the measurement results as a function of gate width.

$$alpha = \frac{neutron\ emission\ rate\ from\ (\alpha,n)\ reactions}{neutron\ emission\ rate\ from\ spontaneous\ fission} \quad (1)$$

Experimental equipment

The counter that was used for these experiments was an Epithermal Neutron Multiplicity Counter (ENMC), and the data acquisition electronics were selected to enable list mode data collection, Figure 2. The ENMC has 121 ^{3}He tubes, which are readout through 27 amplifiers. The default parameters for the ENMC are as follows [6].

Figure 2. ENMC, ALMM, and INCC6 experimental setup.

Table 1. ENMC operating parameters.

Parameter	Value
Efficiency	65%
Dieaway time	22 µs
Gate width	24 µs
Pre delay	1.5 µs
Deadtime coefficient A (E-6)	0.0954
Deadtime coefficient B (E-12)	0.0289
Multiplicity deadtime	36.8
High voltage	1720 V

Note that for the ENMC 1.256xtau = 28.3 us, thus 24 µs is the default setting.

The data acquisition instrument used was an Advanced List Mode Module (ALMM). The ALMM is a multichannel (32) instrument that can produce time-stamped neutron events [7]. The ALMM was controlled using the International Neutron Coincidence Counting 6 (INCC6) software. While INCC5 has been widely used for nuclear material accountancy and international safeguards for decades, a new version 6 has been developed which supports the recording, storage, and analysis of list-mode data [8, 9]. INCC6 also provides the ability to read-in and analyze previously recorded data. The settings that can be varied for analysis of previously measured data include the gate width, predelay, deadtime corrections, and fast accidentals [2]. Note that for all these measurements fast accidentals (FA), which provides faster sampling of the A gate, was enabled; FA sampling improves the precision of the reals measurement [10].

Experimental data

List mode based experimental data was used to quantify the possible improvements that could be obtained with an optimized gate width, and to demonstrate the use of the upcoming INCC6 software with list mode capabilities for this process. The ENMC was used to measure five sources with list mode data for 800+ cycles of 30 seconds each (6.5+ hours). The sources chosen have identical masses with varying impurities and (α,n) production to highlight the effects of optimal gate width. The source characteristics are detailed in Table 2, and the 92-000 source is shown in Figure 3. The experimentally acquired list mode data was reanalyzed with INCC6 to obtain the doubles and triples rates and associated uncertainties for gate widths ranging from 8 to 256 us. Based on this analysis, the uncertainty relative to the minimum value was determined.

Table 2. Measured source characteristics.

Source ID	Pu mass (g)	Pu239 %	Pu-240 %	Type	Measurement time (h)	Approximate alpha
92-000	10.0	94.5	5.2	Metal	7.0	0
86-000	10.0	94.1	5.6	Oxide	6.8	1.6
87-000	10.0	94.1	5.6	Al	6.8	6.5
67-000	10.0	94.1	5.6	PuF4	7.0	121
91-000	10.0	94.2	5.6	Fluoride	7.0	165

Figure 3. The 92-000 metal Pu source.

Optimized Gate Width Results

The doubles and triples statistical uncertainty was plotted as a function of the different gate widths to identify if there were trends based on the source parameters. The behavior of the doubles statistical uncertainty relative to the minimum uncertainty as a function of gate width is shown in Figures 4 and 5. The results show three regions where the uncertainty is: decreasing, flat within statistics, or increasing, with gate width. This suggests that the temporal distribution of pulses can be under or over sampled, with the amount of sampling controlled by the width of the gate. Operationally only a single gate width can be used, and historically, as discussed in the introduction, an exact optimal gate width has been utilized based on analytical calculations. It has long been recognized that a 'broad minimum' exists. This data confirms that concept experimentally by demonstrating there is an optimal region which spans a range of gate widths. However, the data also shows that the optimal region is quite small for high alpha sources, and that the optimal region differs as a function of alpha.

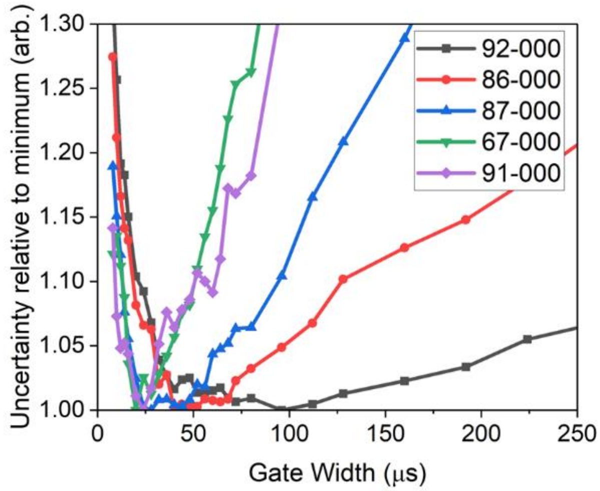

Figure 4. Doubles uncertainty as a function of gate width.

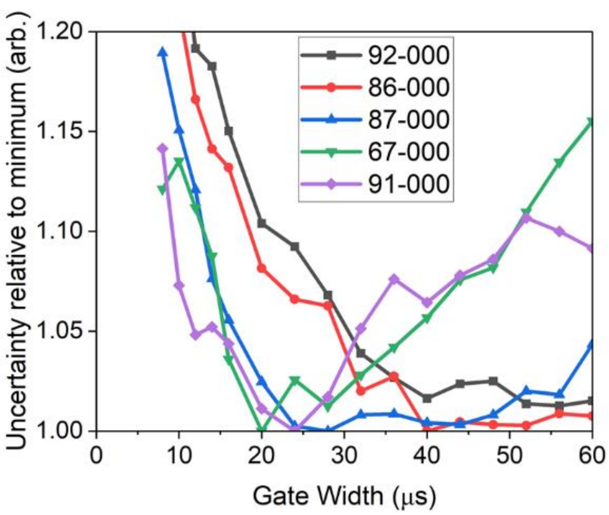

Figure 5. Doubles uncertainty in the region of common detector gate widths (20-60us).

The triples results also follow this 3-region behavior, Figures 6 and 7. The triples exhibit a more rapid increase in uncertainty as the gate width changes beyond the optimal region, which can be seen in Figure 8. This effect results in the optimal range being narrower for triples.

The data show that the optimal range is much larger for the low-alpha metal sample. The lower end of the optimal range also decreases with alpha. In other words, a shorter gate is optimal at higher values of alpha and a longer gate is optimal at lower values of alpha.

For this analysis the optimal range was defined as the range where the relative uncertainty is equal or less than 1.03 relative to the minimum uncertainty. The selection of 1.03 is to account for statistical fluctuations and is discussed in detail in the next section. The optimal range for the gate width as a function of alpha is plotted in Figure 9 below, which shows the largest and smallest (upper and lower bounds) gates that can be used to achieve a relative uncertainty within 1.03 of the minimum for the doubles and the triples. Notably, the theoretical ideal gate width of the ENMC of 24 μs is too small for several of the sources used.

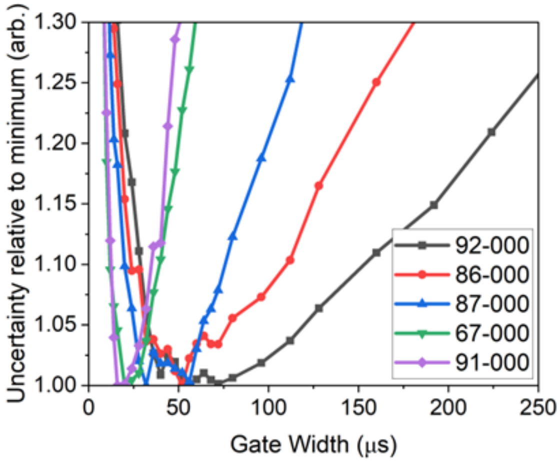

Figure 6. Triples uncertainty as a function of gate width.

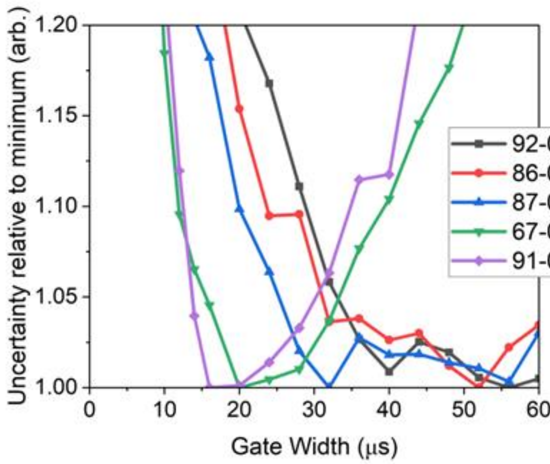

Figure 7. Triples uncertainty in the region of common detector gate widths (20-60us).

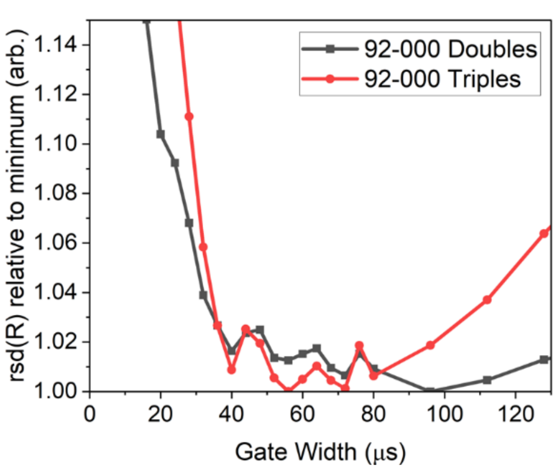

Figure 8. Comparison of uncertainty for doubles and triples rates of the 92-000 metal source.

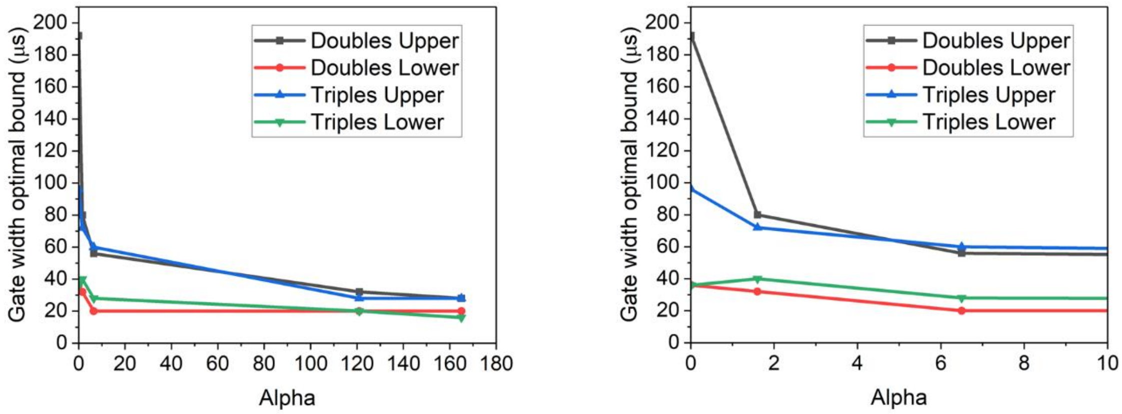

Figure 9. Optimal sampling gate width bounds as a function of item alpha (left) and zoomed in to show the region relevant to most items: oxide and metals with an alpha of 0-2 (right).

In fact, there is no single gate width which is within the optimal region for all sources. The longest gate width within the optimal region for the high alpha sources, 28 µs (the same for doubles and triples), is shorter than the shortest gate width within the optimal region for the low alpha sources, 36 µs for doubles and 40 µs for triples . The data is presented in Table 3. Fortunately, with list mode, a single gate width is not necessary for operation of a neutron assay detector.

Table 3. Optimal gate width bounds for each source. The largest minimum gate and smallest maximum gate are highlighted, showing that no gate width selection is optimal for all sources.

		Optimal gate width range (µs)			
Source ID	Alpha	D min	D max	T min	T max
92-000	0	36	192	36	96
86-000	1.6	32	80	40	72
87-000	6.5	20	56	28	60
67-000	121	20	32	20	28
91-000	165	20	28	16	28

If the measurement gate width is chosen to be optimal for the individual source, large reductions in relative uncertainty can be achieved. This is especially true for sources with low alpha which do not follow the assumption of A>>R used to calculate the traditional gate width of 24 µs. The improvement, defined as the percent increase in the relative uncertainty for 24 µs compared to the gate width with the lowest uncertainty, as a function of alpha, is given in Figure 10. The improvement is greatest at the lowest alphas and reaches as high as 17% for triples and 9% for doubles.

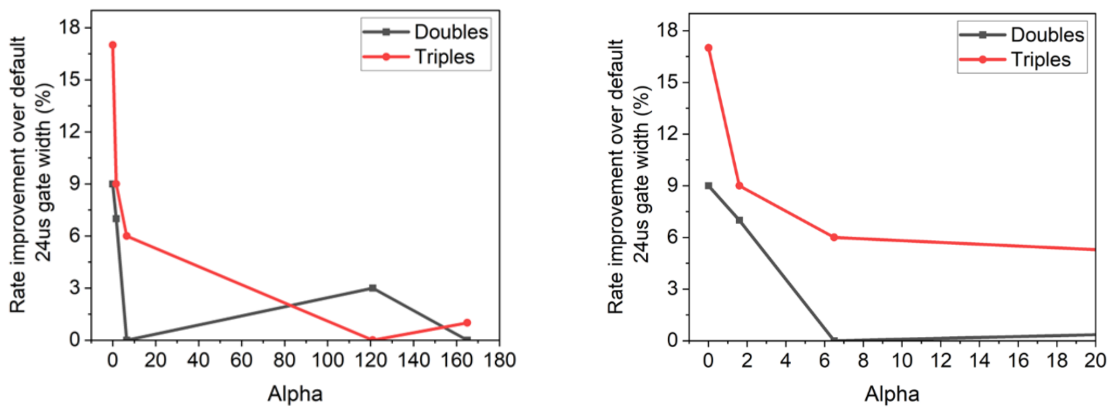

Figure 10. Percent improvement by choosing the optimal gate width instead of 24 µs as a function of alpha (left) and zoomed in to show the region relevant to most items: oxide and metals with an alpha of 0-2 (right).

<u>Statistical analysis</u>

The measurements used in this paper were at least 6.5 hours long for each source, with a minimum of 800 cycles of 30 seconds each. This resulted in clear trends in the results and an optimal region defined as the region where doubles uncertainties were within 3% of the minimum.

The 92-000 measurement data was broken into 15 measurements of 67 cycles each (28.5 minutes) to evaluate the behavior for a more typical measurement time. The average and 2-sigma standard deviation for each gate width is plotted in Figure 11.

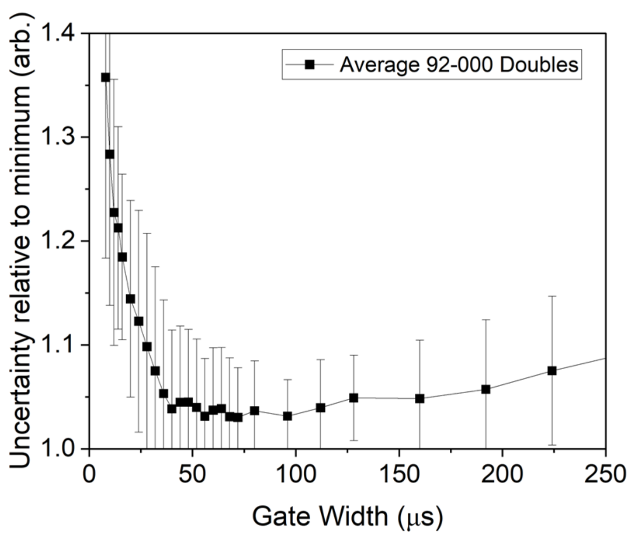

Figure 11. Uncertainty relative to minimum for the metal 92-000 source doubles averaged over 15 measurements of 28.5 minutes each.

The figure shows that, for any given 28-minute measurement, the gate width with the lowest doubles uncertainty will fall between 28 µs and 192 µs (gates for which the average minus 2-sigma bounds 1.0). This is an expected result and matches the 6.5-hour measurement almost exactly (an optimal range of

36 µs to 192 µs). However, to clearly define the boundary of the optimal region, the longer measurement was needed. Also, for any given measurement, a gate width other than the one utilized may have a significantly lower statistical uncertainty.

Conclusions

The optimal gate width for coincidence and multiplicity counting has long been reported as 1.256x the dieaway time, τ, based on analytical calculations. These calculations are optimized for high alpha sources and do not consider fast accidentals sampling. List mode measurement capabilities, enabled by the Advanced List Mode Module (ALMM) electronics and INCC6 software, facilitate the experimental collection and re-analysis of neutron data at a range of gate widths.

This work measured a variety of sources with different (α,n) neutron production rates to experimentally determine the doubles and triples rate statistical uncertainties as a function of gate width. An ideal range of gate widths that minimized the uncertainties (a 'broad minimum') was found for each source. While this range does include the 1.256xτ rule of thumb for high alpha sources, for more common low alpha sources (oxides and metals), the ideal gate width range was significantly larger than 1.256xτ. In fact, the optimal range did not overlap for all sources. In other words, no single gate width falls within all of the optimal ranges.

Therefore, instead of using a single gate width as a fixed detector parameter for every measurement, it may be ideal to adjust the gate width used on an individual measurement basis. Using list mode capabilities, the ideal gate width can be determined for each item individually after the measurement data is collected. Choosing an optimal gate width was found to reduce the doubles and triples uncertainty by up to 9% and 17%, respectively, relative to using the default gate width. Analysis software like INCC6 could automatically find the minimum uncertainty for every measurement, resulting in smaller random errors or reducing the required measurement time for NDA measurements in most applications. This capability could improve the efficiency and effectiveness of safeguards and MC&A programs at nuclear facilities across the world.

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