EXAMINATION OF DIGITAL-DELAY ROSSI-α FOR ^{252}CF-DRIVEN HIGHLY ENRICHED URANIUM USING ORGANIC SCINTILLATORS

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ABSTRACT

Neutron noise techniques constitute several analysis methods applicable to non-destructive assay. One technique is the Rossi-α method to calculate the prompt neutron decay constant (α) or its inverse, the prompt neutron period ($1/\alpha$), for assemblies of fissionable material. This work evaluates a high-data-throughput measurement at the National Criticality Experiments Research Center (NCERC) with organic scintillators measuring a subcritical assembly of highly enriched uranium (HEU) metal (93% ^{235}U). The assembly comprises hemi shells stacked together to form fully closed shells and is driven by a ^{252}Cf source at the center. The assembly is a total of 59.85 kg HEU and a k_{eff} of 0.98, calculated with MCNP6.2 KCODE. Measurements were acquired with a three-by-four array of 5.08-cm-diameter by 5.08-cm-length trans-stilbene crystals 166 cm from the assembly center. Two types of coincident binning methods are used to build the Rossi-α distribution of coincident neutron detections: type 1 binning, also known as *any-and-all* forward time differences, and type 1 binning with a *digital-delay* technique that is analogous to the use of delay cabling in 1950-60's Rossi-alpha experiments. The *digital-delay* technique disregards same-detector coincidences and once all nearest time coincidences are collected between all detectors after a trigger, a time delay of 0.75 µs is implemented. The measured prompt neutron decay constants for both techniques are calculated from single exponential fits and the two methods are compared. *Any-and-all* forward time differences shows an apparent timing discontinuity near 500 ns time differences. This timing discontinuity interferes with the fitting method used to calculate the prompt neutron decay constant. The *digital-delay* technique mitigates the artificial timing discontinuity and removes the disagreement of the fit. Future work will model the time-dependent detector response to discern why this timing discontinuity occurs, discern how the *digital-delay* technique reduces the amplitude of this timing discontinuity, and apply this method to critical assembly measurements to ultimately confirm the recommendation to use the *digital-delay* technique for high-data-throughput measurements.

INTRODUCTION

Neutron noise techniques involve analyzing the time-dependent emission of fission neutrons from single and chain fission events [1]. These techniques may be used to estimate the mass of special nuclear material and infer the multiplying behavior of fissioning assemblies. The Rossi-α method is a neutron noise method that analyzes the time difference between coincident prompt neutron signals to estimate the prompt neutron decay constant (α) of a fissioning assembly [2], [3]. This method was developed prior to the advanced digitization capabilities of radiation detector waveforms. When the Rossi-α method was developed, the resultant time difference histograms were calculated with specially designed logic timing circuitry with set time difference bin widths and set maximum time differences for a given measurement. Due to the exponential growth of computing storage and processing capabilities, it is possible now to analyze digital neutron times with multiple different parameter settings and methods for compiling the neutron detection time-difference distribution. Digital time stamps offer increased statistics and modularity, but the acquisition systems used for full waveform radiation measurements still have an upper limit and may be overwhelmed by large data acquisition rates. Overwhelmed detectors may exhibit non-physical artifacts in time-dependent measurement analysis. This paper investigates a post-processing technique to mitigate one of these artifacts. The methods are investigated using a measurement of a large quantity of highly enriched uranium interrogated by ^{252}Cf. The particular assembly measured has a prompt neutron period (α^{-1}) on the scale of hundreds of nanoseconds. This requires a detector with neutron sensitivity and fast timing capabilities, motivating the use of organic scintillators for this work.

BACKGROUND AND THEORY

This section describes the "Type 1" binning method for Rossi-α from Hansen [2] in the context of digital neutron detection times, how the "Type 1" method might be adjusted to match the analog timing circuits implemented at the time of publication for the measurement in [4], and the expected shape of the resulting time difference distributions.

"Type 1" binning is defined with Figure 1 in [2]. Hansen does not specify exactly how to interpret this diagrammatic explanation, but in this work, we assume "Type 1" to represent the recording of *any-and-all* forward neutron detection time differences.

In Orndoff's measurements in [4], he details the detection system as two detectors connected to a coincident timing circuit with a digital delay of 0.5-0.7 µs. In this system, only the forward time differences between the two detectors, or the "cross-correlated" time differences, were recorded. Additionally, after a cross-correlation event, the an analog delay was implemented to prevent a coincidence of one detector with itself, or "auto-correlated" time differences. During the analog delay, no coincidences were recorded.

Organic scintillators do not present a significant dead time in radiation response in comparison to neutron capture-based detectors (dead time of several microseconds), but the light collection time for each detection (on the scale of hundreds of nanoseconds) can interfere with these time-difference methods observing fissioning assemblies with a prompt period (α^{-1}) on the same time scale. Because of the minimum light collection time, a single detector may be considered "dead" when it is triggered and sampling a waveform. For this reason, correlating a detector with itself may cause unexpected timing distributions.

The description of Orndoff's method and the possible issues with organic scintillators in high-count-rate environments motivates the *digital-delay* technique in this work, which applies *any-and-all* forward neutron time differences with several restrictions. All auto-correlation events are excluded. A digital delay of 0.75 µs is applied after all nearest time cross-correlation events are recorded following a neutron signal trigger. A time difference in this 12-detector array is not considered if the trigger detector is cross-correlated with a another detector multiple times. If detector 2 is triggered and coincident with detector 8 twice in the same time separation limit, the later coincidence is ignored and the first or "nearest" coincidence is the only one recorded in the subset.

Regardless of the method used, the expected distribution of forward neutron time differences

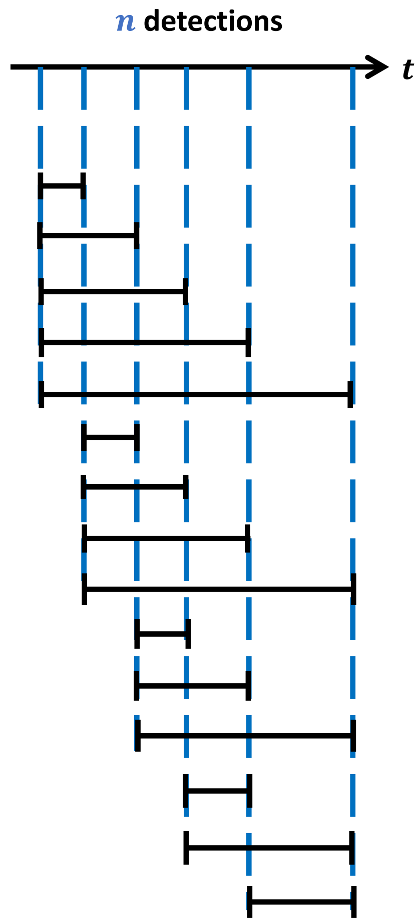

Figure 1. A schematic based on [2] detailing the "Type 1" neutron time difference method. In this work it is interpreted as any-and-all forward neutron detection time differences.

(Δt) is

$$p(\Delta t) = Ae^{\alpha \Delta t} + B, \tag{1}$$

where $Ae^{\alpha \Delta t}$ represents the time-difference behavior of correlated prompt neutrons, α denotes the prompt neutron decay constant, and B represents the chance coincidence magnitude [5].

EXPERIMENTAL SETUP

The Rocky Flats (RF) are stackable uranium hemispherical (hemi) shells of highly enriched uranium (HEU, 93% ^{235}U) housed at the National Criticality Experiments Research Center (NCERC). In this measured assembly, the innermost hemi-shell pair had an inner diameter of 3.01 cm and the outermost hemi-shell pair had an outer diameter of 9.33 cm for a total of 59.85 kg of HEU [6] with an estimated effective criticality, or k_{eff}, of 0.98, calculated with MCNP6.2 KCODE [7]. The configurations were stacked and lifted together remotely during measurement [8].

The scatter-based detection system was a 3-by-4 array of 5.08-cm-diameter by 5.08-cm-thick trans-stilbene crystals aligned with the center of the assembly [5], [9]. The OSCAR array was shielded with tin-copper graded shielding [10] on the front and the front face of the array was 166 cm from the center of the assembly. The detection system acquired waveforms of 288 ns in length for all detectors. During measurement, a ^{252}Cf source emitting approximately 1×10^6 neutrons per second was placed in the center of the RF shells and the assembly was closed for a 60-minute measurement.

PRELIMINARY RESULTS AND ANALYSIS

Using the *any-and-all* and *digital-delay* techniques, we analyzed all neutron detections with a bin width of 30 nanoseconds and a reset time of 1,980 ns. The resultant distributions are in Figure 2. The *any-and-all* distribution shows a small relative increase in coincidence rate at a time difference just below 500 ns that does not appear to follow the expected exponential shape, while the *digital-delay* distribution does not exhibit this timing discontinuity.

Each distribution was fit using a non-linear least-squares regression applying Equation 1. All fits ignored the first bin (30 nanoseconds) of the time difference distribution to remove the effect of detector cross-talk and other electronic artifacts like signal transmission time [11]. The distributions constructed with each binning method were each fit in three ways: the full distribution, early region, and late region. The early region was defined as the region between 50 and 400 ns time differences. The late region was defined as the region above 500 ns time differences.

The prompt neutron decay constant, α, can be understood equivalently by the inverse, the prompt neutron period, α^{-1}. From Figure 3, we note the full distribution fit α^{-1} one standard deviation uncertainty overlaps the one standard deviation uncertainty of α^{-1} for the early region fit but does not for the late region fit for the *any-and-all* distribution. For the *digital-delay* distribution, the full α^{-1} one standard deviation uncertainty overlaps the one standard deviation uncertainty of α^{-1} for both the early and late region fits. Notably, the α^{-1} estimate for the early region increases by less than 1 ns from the *any-and-all* to *digital-delay* distributions and α^{-1} estimates for the full distribution and late region both decrease by approximately 10 and 5 ns respectively.

CONCLUSIONS AND FUTURE WORK

We presented two methods of neutron detection time difference calculations for the Rossi-α method applied to digital detection times. The first method interprets the "Type 1" method simplistically as *any-and-all* forward time differences but does not account for timing discontinuity issues caused by digital acquisition systems in high count rate scenarios. By mimicking previous analog acquisition systems through imposing additional restrictions on *any-and-all* for cross-correlation, nearest time differences, and a digital time delay, the high count rate effects on the Rossi-alpha method for the near critical, ^{252}Cf-driven, highly enriched uranium (HEU) measurement were removed. Future work includes applying the *digital-delay* technique to additional delayed critical HEU measurements and fully characterizing the cause of the timing discontinuity in *any-and-all* forward neutron time differences. Detector response simulations will be used to recreate the measured distributions for both methods and digital acquisition restrictions will be considered. Applying and simulating this method for critical assemblies will ultimately confirm the recommendation to use the *digital-delay* technique for high-data-throughput measurements.

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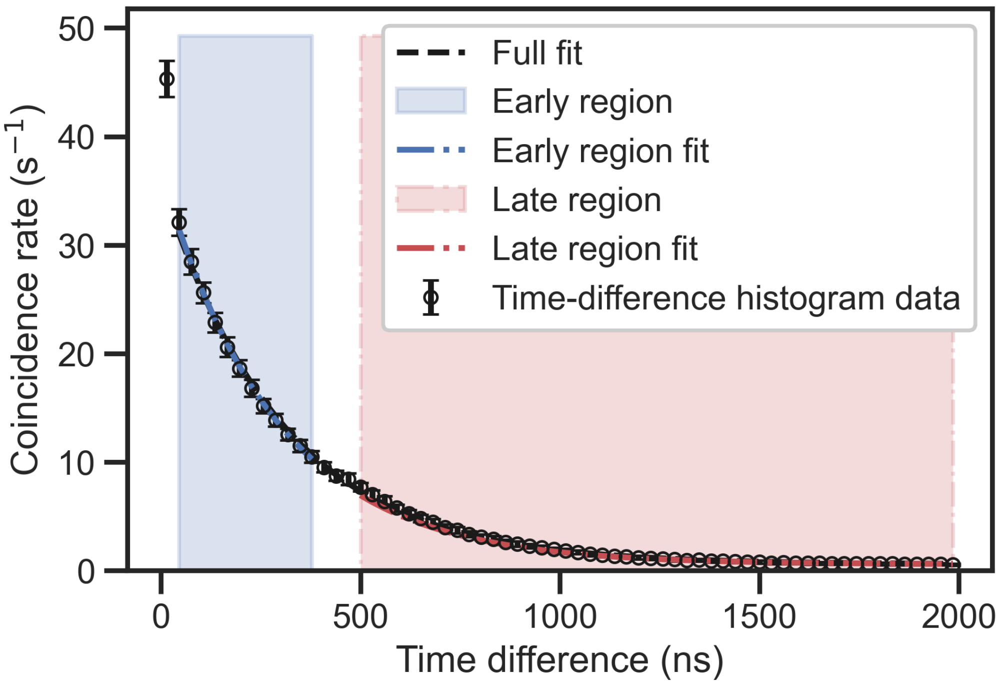
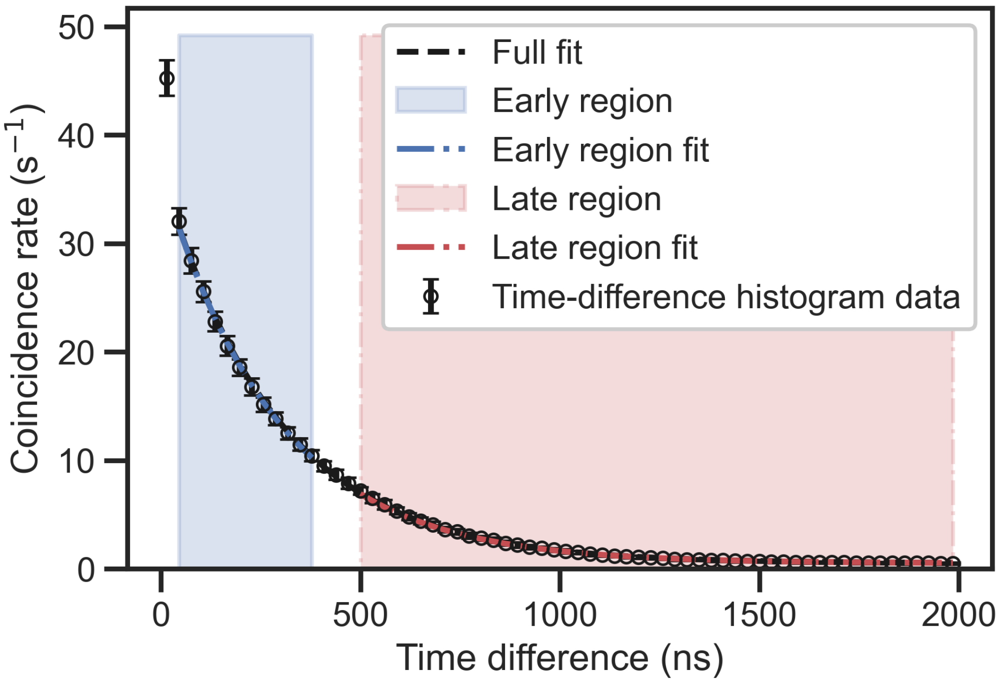


(a)



(b)

Figure 2. The Rossi-α distribution and fits for (a) *any-and-all* forward neutron time differences and (b) the *digital-delay* technique. Note the small discontinuity in the distribution from 400-500 ns in (a) that is not visible in the distribution in (b).

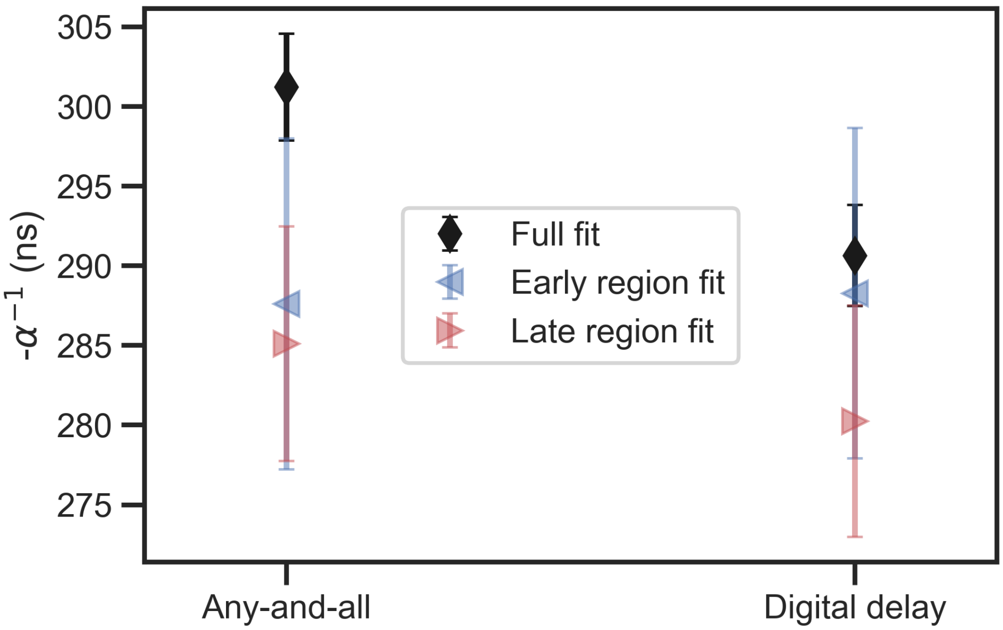


Figure 3. The fit estimates of -α^{-1} for the full distribution, early region, and late region for both methods.

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