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A new method to reduce the statistical and systematic uncertainty of chance coincidence backgrounds measured with waveform digitizers

J.M. O'Donnell

Los Alamos National Laboratory, Los Alamos, NM 87544, USA

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ABSTRACT

A new method for measuring chance-coincidence backgrounds during the collection of coincidence data is presented. The method relies on acquiring data with near-zero dead time, which is now realistic due to the increasing deployment of flash electronic-digitizer (waveform digitizer) techniques. An experiment designed to use this new method is capable of acquiring more coincidence data, and a much reduced statistical fluctuation of the measured background. A statistical analysis is presented, and used to derive a figure of merit for the new method. Factors of four improvement over other analyzes are realistic. The technique is illustrated with preliminary data taken as part of a program to make new measurements of the prompt fission neutron spectra at Los Alamos Neutron Science Center. It is expected that the these measurements will occur in a regime where the maximum figure of merit will be exploited.

1. Introduction and Motivation

The impact of backgrounds on the statistical significance of an experiment is of such importance that Knoll discusses it in his seminal book, *Radiation Detection and Measurement*, just as soon as sufficient statistical background is presented to understand the subject [1]. One of the compromises in performing an experiment is to reduce the amount of time spent taking foreground data (and losing counts and statistics), to take background data. If too much time is spent on the background measurement, then valuable foreground statistics are lost. On the other hand, if insufficient background data are obtained, the quality of the foreground data is compromised by a poor background subtraction. In the book, Knoll presents an expression for the optimal division of time between the two stages of data collection. The question of systematic changes between the two separate measurements is not considered – but is often apparent, for example if a background normalization factor has to be applied during the data analysis. The complications introduced by backgrounds warrant all reasonable attempts to remove the background.

Over the years the coincidence technique has proven to be a powerful method to reduce or even remove large backgrounds. Knoll also discusses the nature of chance coincidences as a source of background in coincidence experiments, and presents a simple formula to estimate the chance coincident rate. The formula is traditionally used to help design layouts for experiments, and provide estimates for the quality of the data when setting up and experiment. The formula for the rate of chance coincidences, r_γ, between two detectors, counting at rates r_a and r_b, during a coincidence time window with width, Δ_t, is

$$r_\gamma = r_a r_b \Delta_t. \tag{1}$$

A key concept in the derivation of Eq. (1) is the dead time, t_d, of the detector, electronics and the data acquisition system (DAQ), even though t_d is not explicit in the formula. Eq. (1) is only valid if $r_a t_d \ll 1$ and $r_b t_d \ll 1$.

While Eq. (1) is well known, we are not aware of any analyzes using it to measure the detailed background shape in a coincidence measurement, presumably due to the difficulty in measuring r_a and r_b reliably. High singles rates impose challenges in acquiring, saving and analyzing complete data sets using an event-triggered DAQ with very real dead-time concerns.

The current work is motivated by the increasing use of flash digitizers running semi-continuously (waveform digitizers), with waveform analysis capabilities on board, to build high throughput DAQs with no contribution to dead time (see e.g. [2–4]). When combined with computers with large storage areas it is now realistic to record complete data sets of all the signals from all the detectors with dead time due only to signal overlap (pileup) in the detector and preamps. Coincidences are identified, in software, later in the analysis.

With such a DAQ we show that Knoll's expression to estimate chance coincidence rates can now be used to determine a bin-by-bin

E-mail address: odonnell@lanl.gov

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measurement of the background obtained simultaneously with the foreground. In addition to reducing systematic uncertainties, this allows us to obtain the maximal signal statistics, and it will be shown yields a very small statistical uncertainty on the background measurement. The question of how much time to spend on the foreground and background measurements becomes trivial – do both all the time!

Before proceeding, we rewrite Eq. (1) in terms of the counts observed in an experiment, which also allows us to easily quantify the statistical uncertainty. The numbers of counts, a and b, obtained in each detector, and summed over N measurements, are then related to the measured singles rates by $a = r_a N \Delta_t$ and $b = r_b N \Delta_t$, and the number of chance coincidences, γ, in the time-difference window, Δ_t, is then

$$\gamma \pm \sigma_\gamma = \frac{ab}{N} \pm \sqrt{\frac{ab(a+b)}{N^2}} \tag{2}$$

where σ_γ, the statistical uncertainty on γ, assuming Gaussian statistics for a and b.

In the next two sections we briefly describe an experiment being developed to measure the prompt fission neutron spectrum (PFNS) on ^{239}Pu [5], and then in more detail, two possible analysis procedures which use Eq. (2) to estimate backgrounds for this experiment. In the following section we contrast this approach with more traditional methods for measuring backgrounds – resulting in the derivation of a figure of merit for the new method of analysis. There then follows a comment on the data-acquisition requirements to obtain a data set which is complete enough to apply the current technique (and a numerical validation of $r_a t_d \ll 1$ and $r_b t_d \ll 1$ for the example experiment). Further formulas derived from Eq. (2), and which are needed to implement a full analysis, are presented in a short series of appendices.

2. Example experiment with complicated backgrounds

Data for outgoing fission neutrons from neutron induced fission of ^{239}Pu are used to illustrate the techniques discussed here. The coincidence nature of the experiment arises from detecting one of the fission fragments together with a neutron generated in the fission process. The detection of a fission fragment implicates the timing properties of the incoming neutron.

The data were acquired as part of the development for the PFNS measurements currently being performed at the WNR/LANSCE neutron spallation source [6]. A conceptual figure of the experiment is shown in Fig. 1. Beam delivery was structured on two time scales (Fig. 2): micro pulses of protons (each making their own timing signal, t_0, and forming their source of spallation neutrons) occur at nominal 1.8 μs intervals; and macro pulses, being groups of 347 micro pulses, separated by several milliseconds. Only two of every three macro pulses were delivered to WNR.

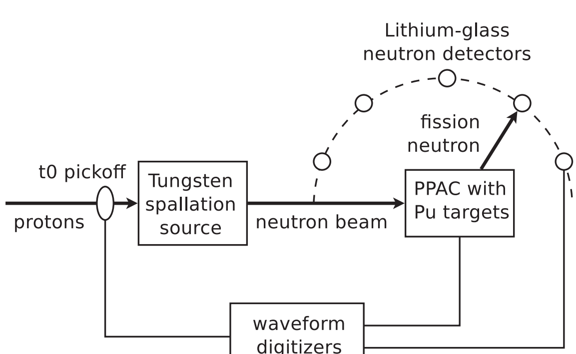

Fig. 1. Conceptual layout for a two-arm time of flight ^{239}Pu $(n;f,xn)$ experiment, detecting fission fragments in a parallel-plate avalanche counter (PPAC), (which implicates the timing of an incoming neutron, with respect to the neutron production time signal from the t_0 pick off), and fission neutrons are detected in the lithium glass neutron detectors.

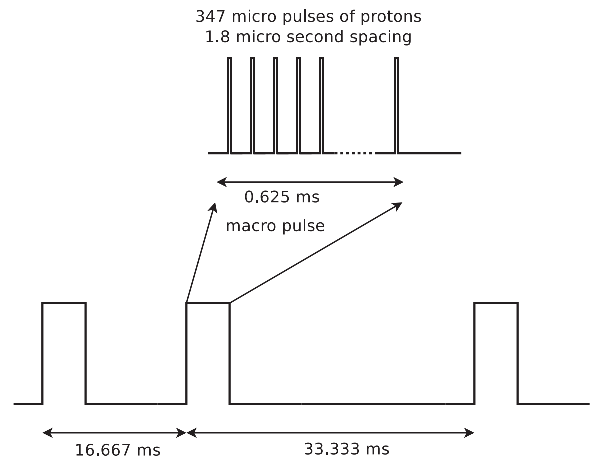

Fig. 2. Structure of the proton beam to WNR.

Model ZT4441-DP-PXI digitizers [7] (sample rate 400 Ms^{-1}) were used to acquire 1 ms long waveforms spanning the duration of complete macro pulses. Triggers for most of the digitizers were distributed across a PXI bus from a self-triggering digitizer receiving the t_0 signal. ZT1000PXI cards [7] enabled distribution of the trigger and a stable reference clock between PXI crates. Up to 22 lithium-glass detectors and digitizer channels were used to detect the outgoing neutrons [8]. A further ten digitizer channels processed the signals from a multi-segment parallel-plate avalanche counter (PPAC) for detecting fission fragments [9]. Each waveform was analyzed on board the digitizer using custom firmware, to generate a list of parameters such as a time stamp, the baseline height, and two integrals of the peak area at different time offsets from the peak position, for all the peaks found in the waveform. The lists of parameters were read from each digitizer across the PXI bus into computer memory for storage and further processing, before preparing the digitizers to process another macro pulse.

The times within a macro pulse of individual peaks in the t_0, PPAC and lithium-glass signals are denoted as t_0, t_f, and t_n, respectively; and the lists of these times as reported by the digitizers are denoted $\{t_0\}, \{t_f\}$, and $\{t_n\}$, respectively.

Backgrounds from several sources are present in the data. Some of the more significant sources are: (1) fast neutrons generated from interactions other than fission from a particular sample foil; (2) a "sea" of thermal and epithermal neutrons (see the rising and decaying baseline in the top panel of Fig. 3); (3) sensitivity of the neutron detectors to gamma rays; and (4) a small residual sensitivity of the PPAC to the large alpha decay rate of the plutonium samples (Fig. 3, lower panel).

These backgrounds remain significant, even after applying some simple background reduction cuts, such as a cuts to separate neutrons from gamma rays in the lithium-glass detectors (exploiting the +4.78 MeV Q-value of the ^{6}Li$(n,t)\alpha$ reaction), and also PPAC pulse-height cuts to optimize fission–alpha-decay separation. We anticipate using a more complete set of cuts for a final analysis of the data from these experiments, but we still expect many components of the background to remain.

3. Coincidence analysis

Given the lists of time stamps, $\{t_0\}, \{t_f\}, \{t_n\}$ for the singles data from each detector, two methods of coincidence analysis are