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Revisiting the form of dead time corrections for neutron coincidence counting

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ABSTRACT

A standard nondestructive assay technique for determining the mass of plutonium in an item is passive neutron coincidence counting. In passive neutron coincidence counting, the dead time or rate loss corrections for the singles and doubles neutron counting rates are routinely made using empirical relationships that are based on the design and performance of the individual counter used to make the measurements. The empirical methods were developed ahead of any supporting theory for dead time losses and have worked well to date for the majority of safeguards measurement scenarios. Modern applications using highly efficient systems with short neutron lifetimes together with the challenges posed by highly multiplying items mean dead time corrections of higher fidelity are needed. While many attempts have been made to develop dead time corrections that are based on the physical principles of the measurements being performed, these corrections have often been found to be difficult to implement in a real system. For instance, Matthes and Haas developed an approach in 1985 which did not gain favor largely because the form of the doubles correction apparently required numerical integration which was difficult to implement with the computer technology of that time. A recent review into the approach that was developed by Matthes and Haas has determined that a straightforward analytical expression can be derived for the doubles correction that is similar to the singles rate correction that was developed in their original work. An analysis of the expressions is presented here to show how they relate to the traditional empirical methods. Further, we illustrate their implications and limitations. For instance the empirical methods do not address within burst losses i.e. rate related losses due to the correlated neutron bursts from fission, whereas the Matthes and Hass expression for singles counting does exhibit such an effect.

1. Introduction

Passive neutron coincidence counting (PNCC) is a method for the nondestructive assay of special nuclear material undergoing spontaneous fission (Ensslin et al., 1978) to determine the spontaneous fission rate within the item. An assay is performed using shift register logic (Swansen, 1985) to determine the correlated neutron pairs counting rate, known as the reals or doubles, in addition to the totals or singles neutron counting rate. The essence of the method is that the doubles rate distinguishes time correlated neutrons, a signature of fission, from neutrons with random emission (and arrival) times such as those produced by (α,n) reactions.

The most widely applied method to correct for dead time losses in the singles and doubles rates is the use of empirical relationships (Krick and Menlove, 1979; Croft et al., 2011). This has served the safeguards community extremely well for over 30 years. However, there has been a trend to build detection systems of both higher efficiency and shorter characteristic die-away time, which results in a greater chance for detecting higher multiplets and concentrates the correlated events over a shorter time period. Gradually the regime under which the empirical dead time methods were developed has changed and it is natural to ask if more sophisticated methods are needed. The range of items being measured (higher self-multiplication and higher (α,n) production) also challenge the algorithms to a greater extent than previously. Further, one would also like a unified approach to dead time corrections, which covers not only singles and doubles, but also triples and higher order multiplet rates which are part of the neutron multiplicity counting method that is typically used to measure impure or highly multiplying items (Ensslin et al., 1998).

The current empirical forms of the dead time correction factors are as follows:

$$CF_D = e^{\delta_D \cdot S_m} = e^{(a+b\cdot S_m)\cdot S_m} \tag{1.1}$$

$$CF_S = e^{\delta_S \cdot S_m} = e^{\frac{1}{4}(a+b\cdot S_m)\cdot S_m} = CF_D^{1/4} \tag{1.2}$$

where CF_D is the dead time correction factor for doubles rate; CF_S is the dead time correction factor for singles rate; S_m is the observed

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or measured singles rate (not corrected for dead time losses); a and b are empirical dead time parameters (assumed constant for a given detector system); and the doubles and singles effective system dead time parameters δ_D and δ_S respectively, are defined by these expressions in terms of a and b, and S_m.

The form and parameterization of the doubles dead time parameter, δ_D, were initially measured (Menlove and Swansen, 1985) by plotting the normalized logarithm of the net (i.e. corrected for accidentals or chance coincidences) doubles rate from a ^{252}Cf source as a function of the observed singles rate S_m. The observed singles rate was varied by adding AmO_2/LiH (α,n) sources, which boost the random (not temporally correlated) neutron rate. This approach suggested describing δ_D in terms of a low order polynomial of S_m to accommodate deviations from linearity. The fission system is constant for all ^{252}Cf sources of similar construction (isotopic composition and encapsulation); therefore the two free parameters a and b may also be obtained by counting ^{252}Cf sources of various strengths and requiring the ratio of dead time corrected doubles to the dead time corrected singles, D_c/S_c, to be constant. This doubles dead time correction factor has a specific functional form which one would like to justify at a more fundamental level. For instance, the empirical form for the doubles correction rate consists of a factor of 1/4 applied to δ_D to derive δ_S. While it is unclear how the factor of 4 for the ratio δ_D/δ_S was arrived at by the early workers in the field, empirical evidence accumulated over the years has shown that when allowed to vary the 'best' value is system specific and may vary roughly between 3.6 and 4.4 (Croft and Yates, 1999).

2. Analysis

Starting from the one-dimensional (1-D) Rossi-α distribution, Matthes and Haas (1985) outline how rate loss corrections for a fixed extending dead time model can be derived using conditional probability theory for a neutron coincidence counter (shift register pairs or reals) characterized by a single exponential die-away time of the neutrons within the system, which dominates the temporal behavior of the item. While their original work did not produce a convenient implementation of the doubles correction factor which flows from their analysis, and was marred by some minor typographical mistakes, the work was pioneering in its use of conditional probability theory to determine rate loss corrections for passive neutron coincidence counting. By performing a complete mathematical review of their analysis technique, the following expressions were derived for the dead time corrected rates:

$$S_m = S_c\cdot\left(1-\frac{D_c/f_d}{S_c}\cdot\frac{d}{\tau}\right)\cdot\exp\left[-S_c\cdot d\cdot\left(1-\frac{1}{2}\cdot\frac{D_c/f_d}{S_c}\cdot\frac{d}{\tau}\right)+0\left(\left[\frac{d}{\tau}\right]^4\right)\right] \quad (2.1)$$

$$D_m = D_c\cdot\left(1-2\cdot S_c\cdot d\cdot\left[1-\frac{D_c/f_d}{S_c}\cdot\frac{d}{\tau}\cdot\left(1+\frac{1}{2}\cdot\frac{\theta_2}{\theta_1}\right)\right]\right)\cdot\exp\left[-2\cdot S_c\cdot d\cdot\left(1-\frac{D_c/f_d}{S_c}\cdot\frac{d}{\tau}\right)+0\left(\left[\frac{d}{\tau}\right]^4\right)\right] \quad (2.2)$$

where S_m and S_c are the measured and dead time corrected singles rates, respectively; D_m and D_c are the measured and dead time corrected doubles rates, respectively; f_d is the doubles signal triggered interval gate utilization factor; d is the dead time parameter for the system; and τ is the $1/e$ detector die-away time constant. The functions θ_1 and θ_2 appearing in (2.2) are defined below. The dead time is assumed fixed and to be of the extending (paralyzable) type under the additional assumption that there is only a single dead time element present in the system. In other words, it is a model of a single neutron detector; whereas typically real systems are composed of clusters of neutron detectors connected to a single charge amplifier/discriminator and the outputs of the logic pulses from the individual amplifiers are combined, often through a derandomizer (to prevent the width of the logic pulse itself adding dead time and spacing counts from different channels to allow the circuitry to accept them without loss), and fed into a shift register coincidence counting module. Modern systems may use list mode data acquisition and record the individual pulse trains which are then combined and analyzed off-line. For the dead time model to apply, one can try to design detector systems that conform to the point and dead time correction models. Explicitly, the Matthes and Haas theory of dead time correction is founded on the 1-D Rossi-α distribution, $p(t|0)\cdot dt$, which is the conditional probability that a neutron will be detected in the interval dt about time t given that there was an event recorded at time $t = 0$. The form adopted for the average capture time probability (Williams, 1974), written in the notation of this paper, is:

$$p(t|0)\cdot dt = \left[S_c+\frac{(D_c/f_d)}{S_c}\cdot\frac{e^{-t/\tau}}{\tau}\right]\cdot dt \quad (2.3)$$

We have truncated the dead time correction expansions at the term $0([d/\tau]^4)$ appearing in the exponential functions of the expression; choosing to use d/τ as a convenient dimensionless parameter for characterizing the order of the expansion. The ratio d/τ is typically in the range 0.001–0.004 for ^{3}He proportional counter based PNCC systems in routine operation today. The polynomial terms i.e. the pre-factors or multipliers to the exponential factors are exact within the Matthes and Hass model and so no truncation is needed for these. Within the Matthes and Haas dead time correction model, which rests on the assumption of a pure exponential capture time distribution, we also have:

$$f_d = e^{-T_p/\tau}\cdot\left(1-e^{-T_g/\tau}\right) \quad (2.4)$$

$$\theta_1 = \tau\cdot e^{-T_p/\tau}\cdot\left(1-e^{-T_g/\tau}\right) = \tau\cdot f_d \quad (2.5)$$

$$\theta_2 = \tau\cdot\frac{e^{-2\cdot T_p/\tau}\cdot\left(1-e^{-2\cdot T_g/\tau}\right)}{2} \quad (2.6)$$

where T_p and T_g are the pre-delay and gate width settings respectively, used in the shift register analysis. From these relationships, we find by algebraic re-arrangement the following equality for the case that the detector (rather than the item) dominates the capture time distribution and exhibits a single exponential die-away profile:

$$1+\frac{1}{2}\cdot\frac{\theta_2}{\theta_1} = 1+\frac{f_d+2\cdot e^{-(T_p+T_g)/\tau}}{4} \quad (2.7)$$

This expression also conveniently serves as an implementation (coding) check to direct evaluation. Several important points need to be made concerning these dead time correction expressions: First, for a random neutron source ($D_c = 0$) the expression for the dead time affected singles rate correctly collapses to the exact analytical result for the Poisson pulse train, given by $S_m = S_c\cdot\exp[-S_c\cdot d]$ when $D_c = 0$.

The same result is seen to hold approximately in the limiting case that the pulse train is only lightly correlated and/or when the dead time is vanishingly small in comparison to the die-away time (i.e. when the dead time is small compared to the timescale over which a correlated group of neutrons will be detected). In this