Nuclear Instruments and Methods in Physics Research A 797 (2015) 144–152

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

The impact of gate width setting and gate utilization factors on plutonium assay in passive correlated neutron counting

D. Henzlova [a,*], H.O. Menlove [a], S. Croft [b], A. Favalli [a], P. Santi [a]

[a] Los Alamos National Laboratory, Los Alamos, NM 87545, USA
[b] Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA

ARTICLE INFO

Article history:
Received 18 February 2015
Accepted 27 May 2015
Available online 15 June 2015

Keywords:
Gate utilization factors
Optimum gate width
Neutron multiplicity counting
Plutonium assay
Feynman variance-to-mean

ABSTRACT

In the field of nuclear safeguards, passive neutron multiplicity counting (PNMC) is a method typically employed in non-destructive assay (NDA) of special nuclear material (SNM) for nonproliferation, verification and accountability purposes. PNMC is generally performed using a well-type thermal neutron counter and relies on the detection of correlated pairs or higher order multiplets of neutrons emitted by an assayed item. To assay SNM, a set of parameters for a given well-counter is required to link the measured multiplicity rates to the assayed item properties. Detection efficiency, die-away time, gate utilization factors (tightly connected to die-away time) as well as optimum gate width setting are among the key parameters. These parameters along with the underlying model assumptions directly affect the accuracy of the SNM assay. In this paper we examine the role of gate utilization factors and the single exponential die-away time assumption and their impact on the measurements for a range of plutonium materials. In addition, we examine the importance of item-optimized coincidence gate width setting as opposed to using a universal gate width value. Finally, the traditional PNMC based on multiplicity shift register electronics is extended to Feynman-type analysis and application of this approach to Pu mass assay is demonstrated.

1. Introduction

In Passive Neutron Multiplicity Counting (PNMC) applications, high detection efficiency is typically required in order to detect correlated pairs or higher order multiplets of neutrons emitted by an assayed item [1,2]. The correlated neutron signal is a direct signature of nuclear fissions occurring in the item and can be used to quantify the amount of fissioning material. To achieve high detection efficiency, thermal neutron counters typically utilize a well-type geometry with the central cavity surrounded by one or more rings of thermal neutron detectors (typically ^{3}He filled proportional counters) embedded in high density polyethylene (HDPE). The cavity is enclosed by top and bottom end-plugs made of suitable material (typically HDPE or an assembly of aluminum with HDPE, or graphite) to re-scatter the item-emitted neutrons back into the counter's active volume. Various designs of well-counters are available with performance characteristics optimized for measurements of different items of interest. A detailed overview of existing coincidence and multiplicity well-counters can be found in [1,2]. To characterize the assayed special nuclear material (SNM), the measured multiplicity rates (singles, *S*, doubles, *D*, and triples, *T*) are linked to the item properties (mass, multiplication and relative random neutron contribution from (α,n) reactions, denoted as α) through several assumptions encompassed within point-model [2]. Several well-counter specific parameters are required in order to extract the item characteristics from the measured multiplicity rates. Detection efficiency is an essential parameter and is typically extracted via measurements of well-characterized (i.e. certified by national certification body such as National Institute of Standards and Technology, NIST or National Physical Laboratory, NPL etc.) reference ^{252}Cf sources with uncertainties of typically $\sim$1.5%. To account for differences in ^{252}Cf and Pu neutron emission spectra subsequent re-calibration is typically performed using a well-characterized Pu standard or through application of a Monte Carlo calculated correction factor. The neutron die-away time represents another key parameter characteristic of a given counter design. The neutron die-away time corresponds to the mean lifetime of neutron population in the counter and represents the average time of slowing down and diffusion of neutrons within the counter material before detection or loss via parasitic neutron capture (outside the active volume) or via escape from the detection system. In practice the slowing down times are short compared to the diffusion timescales and do not significantly affect the measured signals, since the detected events correspond to neutrons after the initial slowing down process. Die-away time is a fundamental characteristic of counter

* Corresponding author.
E-mail address: henzlova@lanl.gov (D. Henzlova).

http://dx.doi.org/10.1016/j.nima.2015.05.064
0168-9002/

design and is closely related to the amount of moderating material (typically HDPE) and distribution and intrinsic efficiency of individual thermal neutron detectors within the system. Die-away time determines the optimum operating parameters of a counter as it defines the length of time window (coincidence gate) needed to detect a sufficient fraction of correlated fission events. Short die-away time is desirable in practical applications in order to reduce chance coincidence events that are detected along with the genuine correlated events and thus deteriorate the measurement precision. Although die-away time is a key parameter that defines other essential counter operating characteristics, in practical application it is needed only to determine the gate utilization factors (GUF) that essentially represent correction factors for the use of finite coincidence gate in the counting of correlated events. The decay of the neutron population within the counter is typically approximated by a single exponential with the die-away time as the 1/e decay parameter. Due to the finite coincidence gate width used to perform correlated counting and roughly exponential decay of the neutron population not all correlated neutrons are detected and counted within the selected finite gate width [2,3]. GUF values correct for the 'missing events' and thus effectively extrapolate the detected finite-gate multiplicity rates (S, D, T) to the near-ideal, 'infinite-gate' quantities required in point model expressions. It is therefore the operating coincidence gate width and corresponding GUF values that are essential for counter performance and quality of Pu assay.

The nuclear safeguards community, including the International Atomic Energy Agency (IAEA), traditionally employs multiplicity shift register (MSR) electronics to perform time correlation analysis (TCA) on the neutron detection times (pulse train). In MSR, set of two coincidence gates (of the same width) is used to extract multiplicity rates (D, T): triggered-gate and random-gate. The triggered-gate is opened by each detected neutron and all correlated multiplets within this gate, following a short predelay, T_p, are counted to create a triggered-gate multiplicity distribution. The predelay is a triggered-gate specific parameter that is needed to remove a portion of the pulse train affected by instrumental artifacts (deadtime, baseline shift, etc.) following each trigger pulse and is typically selected to allow sufficient time for these effects to dissipate before the coincidence gate is inspected. The triggered-gate multiplicity distribution contains both genuine as well as randomly correlated multiplets. Contrary to the triggered-gate, the random-gate is opened randomly with respect to the neutron detection times. No predelay is required for this gating scheme. Two approaches can be utilized to generate the random-gate multiplicity distribution: use of sufficiently long delay following the trigger pulse to assure that any correlations with the trigger have dissipated or use of sequence of gates opened at a fixed rate. The latter approach is also known as fast accidentals (FAS) and has been shown to improve the precision of MSR multiplicity rates by up to a factor of $\sqrt{2}$ [4]. The random-gate multiplicity distribution then contains multiplets that are randomly correlated with respect to the trigger pulse and is used to remove this random contribution from the triggered-gate multiplicity distribution. In the MSR, the correlated events from triggered-gate and random-gate are thus combined to extract the genuine correlated multiplicity rates (D, T). This type of analysis (also known as MIXED) employs a finite coincidence gate and the measured D and T rates represent so-called finite-gate multiplicity rates. Triggered-gate GUF values are then required to extrapolate these measured quantities to the corresponding 'infinite-gate' multiplicity rates.

Alternatively, in the field of sub-criticality experiments, Feynman variance-to-mean analysis is more commonly employed. This approach utilizes solely information contained within the random-gate. Similarly as in the case of MSR approach, two methods can be utilized to generate the random-gate multiplicity distribution: use of sufficiently long delay following the trigger pulse to assure that any correlations with the trigger have dissipated or use of sequence of gates opened at a fixed rate. The latter approach is typically employed to perform Feynman variance-to-mean analysis, however, the information contained in the random-gate multiplicity distribution generated using the long delay may also be used to extract correlated events as shown in [5]. A link between the Feynman variance-to-mean analysis and PNMC was recently established and discussed in detail in [5–7] and relies on the realization that multiplicity distribution constructed from series of random-gates can itself be utilized to extract the genuine correlated multiplicity rates. This approach was termed Randomly Triggered Interrogation (RTI). Equivalence between the MSR and RTI approaches for a range of ^{252}Cf sources was experimentally demonstrated [5], suggesting that both approaches can be used interchangeably to extract multiplicity rates (i.e. S, D, T) within PNMC and their potential respective benefits can be further evaluated. Similarly as in the MSR analysis, finite gate width is used to extract the measured correlated multiplicity rates using RTI approach. Corresponding random-gate GUF values are thus required to extrapolate the measured quantities to the near-ideal 'infinite-gate' multiplicity rates.

Theoretical expressions for triggered-gate as well as random-gate GUF values are available [7,8] and generally rely on a single die-away time assumption, derived for an idealized detection system, where neutron population lifetime can be described by a single exponential. The corresponding expressions are written as follows:

$$f_n = \left[e^{-T_p/\tau}\left(1-e^{-T_g/\tau}\right)\right]^{n-1} = f_2^{n-1} \tag{1}$$

$$w_n = \sum_{k=0}^{n-1}(-1)^k \binom{n-1}{k}\left(\frac{1-e^{-kT_g/\tau}}{kT_g/\tau}\right) \tag{2}$$

In these expressions $n \geq 2$, T_p represents predelay, T_g is the selected gate width and τ is the system die-away time.

Realistic systems, however, often utilize several rings of neutron detectors embedded in varying amounts of HDPE and although single die-away time assumption is typically valid to a good degree, multiple die-away time components always exist due to the finite and heterogeneous nature of the system. In safeguards applications it is thus common practice to determine the GUF values for each coincidence/multiplicity counter experimentally, instead of using Eqs. (1) and (2), and to treat them as fixed counter-specific constants. In the standard MSR analysis, expressions for triggered-gate GUF values based on the measured multiplicity rates can be derived assuming a non-multiplying system with no random (α,n) neutron contribution (i.e. a ^{252}Cf neutron source) and correspond to [2]:

$$f_d = \frac{2\nu_{S1}D_{\mathrm{MSR}}}{\varepsilon\nu_{S2}S_{\mathrm{MSR}}} \tag{3}$$

$$f_t = \frac{3f_d\nu_{S2}T_{\mathrm{MSR}}}{\varepsilon\nu_{S3}D_{\mathrm{MSR}}} \tag{4}$$

where S_{MSR}, D_{MSR}, T_{MSR} correspond to deadtime-corrected measured MSR singles, doubles and triples rates, respectively; and ν_{si} ($i=1$–3) represent the first–third factorial moments of the spontaneous fission neutron distribution. Thus it can be seen that f_d and f_t can be extracted directly from the deadtime-corrected measured ^{252}Cf multiplicity rates. It should be pointed out that since the GUF values essentially reflect the die-away time of the system, which is independent of the type of item measured, the use of ^{252}Cf source provides adequate representation of the die-away behavior that can be utilized also for Pu-bearing items. Eqs.