Simulation of Rate-Related (Dead-Time) Losses In Passive Neutron Multiplicity Counting Systems - 8084

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ABSTRACT

Passive Neutron Multiplicity Counting (PNMC) based on Multiplicity Shift Register (MSR) electronics (a form of time correlation analysis) is a widely used non-destructive assay technique for quantifying spontaneously fissile materials such as Pu. At high event rates, dead-time losses perturb the count rates with the Singles, Doubles and Triples being increasingly affected. Without correction these perturbations are a major source of inaccuracy in the measured count rates and assay values derived from them. This paper presents the simulation of dead-time losses and investigates the effect of applying different dead-time models on the observed MSR data.

Monte Carlo methods have been used to simulate neutron pulse trains for a variety of source intensities and with ideal detection geometry, providing an event by event record of the time distribution of neutron captures within the detection system. The action of the MSR electronics was modelled in software to analyse these pulse trains. Stored pulse trains were perturbed in software to apply the effects of dead-time according to the chosen physical process; for example, the ideal paralyzable (extending) and non-paralyzable models with an arbitrary dead-time parameter.

Results of the simulations demonstrate the change in the observed MSR data when the system dead-time parameter is varied. In addition, the paralyzable and non-paralyzable models of dead-time are compared. These results form part of a larger study to evaluate existing dead-time corrections and to extend their application to correlated sources.

INTRODUCTION

In this paper, we discuss a Monte Carlo approach to the simulation of dead-time losses in PNMC systems in place of the conventional point model with semi-empirical analytical correction factors. PNMC based on neutron pulse train time correlation analysis is a widely used non-destructive assay technique for quantifying spontaneously fissile materials such as Pu. The technique is routinely applied to the assay of items including Pu metal, scrap, oxides and residues [1].

Time Correlation Analysis

Neutrons arising from spontaneous fission provide a unique time signature for the identification of nuclides such as the even isotopes of Pu. A multiplicity distribution of neutrons is emitted from spontaneous fission events, with the shape of this distribution governed by the mass of the fissile nuclide and the kinematics of the fission process. Each burst of prompt neutrons (initial plus those induced by fast fission) is emitted within $\sim 10^{-14}$ seconds of the initiating fission event. These neutrons are therefore closely correlated in time.

Passive neutron counting methods for waste assay and nuclear safeguards rely on this time signature to distinguish between time correlated neutrons, from both spontaneous and induced fission in the assay item, and single, random neutrons arising from background events; for example, (α, n) reactions in the surrounding material. Temporal correlations therefore allow neutron measurements to be conducted in the presence of high background.

Standard multiplicity counter designs use He-3 gas filled proportional counters embedded in High Density Polyethylene (HDPE) for the detection of neutrons. Nuclear safeguards measurements are commonly conducted using cylindrical well counters with several rings of He-3 detectors surrounding a central cavity in which the assay item is placed. Neutrons from fission are emitted essentially isotropically and are slowed in the HDPE so that the likelihood of absorption in the He-3 active volume is increased. A cluster of neutrons is slowed and migrates in the moderator retaining the initial time correlation. The detection is therefore spread out in time and amongst the array of He-3 tubes. The use of multiple rows of counters facilitates high efficiency measurements at high speed via the detection of neutrons from individual fission events. The pattern is usually chosen to minimise the spatial and energy dependence of detection and to control the die-away time; for example, with the use of liners such as Cd.

The characteristic time for a neutron, once thermalised, to undergo capture or leak from the system is known as the die-away time, τ, and is characteristic of the specific detector. Note typically the die-away time is measured relative to a neutron trigger and the trigger is likely a thermal neutron. If we trigger from the initiating release of neutrons then a thermalisation time comes into play. Neutron pulse trains are the stream of digital electronic pulses representing the time-stamp of neutron captures in the detector; produced following amplification and discrimination of the analogue signal from the detector output.

Neutron pulse trains are stored in the MSR to carry out time correlation analysis using coincidence gating. This method is based on detection of time correlated events occurring during a gate width T_g following an initial trigger from a detected neutron event occurring at $t = 0$. The probability of detecting a neutron originating from that fission event (correlated in time to the trigger particle) falls approximately exponentially with time for many detector heads; the form of which is given by the Rossi-Alpha distribution [2]. Neutrons from the same fission event as the initial trigger event are detected in the Reals + Accidentals (R + A) gate. Random background events are detected in a delayed gate known as the Accidentals (A) gate and are far apart enough in time so as not to be related to the initial fission event. Counts from the A gate therefore provide a measure of the background of neutron events occurring in the detector but which are not time correlated with the trigger. The [(R+A)-A] tally rate is the Reals coincidence rate also known as the pairs rate.

PNMC is an extension of the two-parameter assay technique of Passive Neutron Coincidence Counting (PNCC) just outlined and involves recording the frequency of different multiplicity events falling within the coincidence gate width. The result is a histogram of events from which the Singles, Doubles and a third measured parameter; the Triples count rate may be calculated. The assay response in each case yields the spontaneous fission strength as an effective (or equivalent) mass of Pu-240. The total plutonium mass can then be determined knowing the isotopic composition of the assay item.

Dead-Time Behaviour in PNMC Systems

Dead-time is the time by which two events must be separated in order to be processed independently. Dead-time can be reasonably well characterised by an overall system parameter which encompasses contributions to the dead-time from the detector, amplifier, signal pile-up at the discriminator and synchronisation losses at the MSR input.

There are two dominant one-parameter idealised theoretical models of dead-time representing the two limiting cases; type I, paralyzable dead-time and type II, non-paralyzable or updating dead-time [3]. Type I dead-time takes the system dead-time parameter to be of fixed value, D following every pulse that is counted. Type II dead-time takes D to extend from every pulse, whether counted or suppressed due to arrival during the dead-time of the preceding pulse. For well defined passive neutron counters operated with fast electronics the major contributor to dead-time is the action of the pulse discriminator (time above threshold) and the closest model is traditionally considered to be the paralyzable model.

The effect of dead-time is to perturb the neutron pulse trains and thus affect the measured count rates, thereby introducing a bias in the final assay result. Singles, Doubles and Triples count rates are increasingly affected by dead-time. The effect is complicated because the input pulse train is not random in time by definition of the assay problem. The higher orders are expected to be affected more since they correspond to the registration of a higher number of events in a time scale commensurate with the die-way time (a higher instantaneous rate). Further the interplay of ‘accidental’ triples is not simply obtained from a mathematical action on the difference histogram but involves the promotion of Doubles into apparent Triples as a result of random pile-up.

In practical terms, increased rate-related losses can arise as a result of an increased count rate due to increased detection efficiency (>60% in modern counter designs) and the assay of greater Pu masses with high self-leakage multiplication or comparatively high (α, n) rate. High event rates lead to a high number of events in a single coincidence gate width and increases the chance of overlapping random events. The precision in the dead-time correction factor may then become the dominant error over the counting precision itself [4].

A MONTE CARLO APPROACH TO THE INVESTIGATION OF DEAD-TIME LOSSES IN PNMC SYSTEMS

The point model is presently the most common approach applied to interpret the MSR data. This model can be replaced by a detailed Monte Carlo simulation to create a pulse train that can be analysed in software including allowance for dead-time losses, as demonstrated in the numerical model described by Bondar [5].

This work has been motivated by the recent work of Croft et al. [4] which recognises that the current semi-empirical analytical approaches to dead-time corrections are inadequate in certain situations of practical interest; for example, the assay of bulk quantities of PuO_2 fuel feed-stock and the measurement of lean impure scrap and waste materials which have both high (α, n) to spontaneous fission yields and high absolute emission rates.

The need for re-evaluation of existing dead-time corrections has meant that work is already being done to try and improve the empirical models. Presented here is a complimentary simulation tool to provide a systematic investigation of dead-time behaviour to support current and future work on the re-evaluation of dead-time correction methods.

Importance of Simulation

This simulation approach allows a full systematic study of dead-time behaviour across a range of input parameters for the MSR, including variation of gate width and pre-delay settings. Additional features may be readily included that are not practical in a real system; for example, the detection geometry can be easily modified to vary the detection efficiency. Count rates can be distributed between different numbers of pre-amplifier boards to investigate the effect of different input channels to the MSR on the dead-time behaviour. This can be used to aid the development of future counter designs.

Simulation reduces the need for physical calibration standards. This is important when high mass calibration sources are becoming increasingly expensive to use in research laboratories, particularly Pu calibration standards. Simulation therefore allows studies of dead-time behaviour in high count rate regimes such as the MHz region, where physical calibration standards may have limited availability. Studying dead-time behaviour in these count rate regimes can be used to test the limits of current dead-time corrections.

A software multiplicity counter also has the advantage that list mode data can be saved so that post-processing of the data can be carried out using many different algorithms. In other words it is not restricted to hardware or firmware pre-processing of the pulse trains.

SIMULATION METHOD

A Monte Carlo method has been used to simulate neutron pulse trains for several Cf-252 sources with a variety of source intensities and with ideal detection geometry, providing an event by event time distribution of neutron captures within the detection system. The action of the MSR electronics was modelled in software to analyse these pulse trains. The method of neutron pulse train generation described in detail here is based on previous work conducted by Swinhoe et al [6]. In the present study our initial aim is to establish the method for later application specific problems.

Neutron Pulse Train Generation: MCNPX

A simple model of an ideal (4π geometric coverage) He-3 neutron detector was created using the transport code MCNPX [7]. The detector was modelled with radius 1000m and density 1.65 kgm^{-3} corresponding to a pressure of 13.5 atm at 300K. A point like Cf-252 spontaneous fission source was modelled to have a small spherical volume and positioned at the centre of the detector. The use of the spontaneous fission source card in MCNPX enables spontaneous fission events to be sampled from the correct multiplicity distribution for the fissile nuclide, a capability which was unavailable in earlier versions. Spontaneous fission neutrons were launched from a point in the centre of the source with energies sampled from a Watt fission spectrum [const.exp(-E/a).sinh($(b.E)^{0.5}$)] with parameters a and b equal to 1.175 and 1.04 respectively and energy E in MeV [7].

Neutron captures in He-3 were tallied using the coincidence capture tally (FT8 CAP 2003). Capture data was written to an output file known as the PTRAC file for post-processing in software. The PTRAC file contains four columns of data listing the particle history number, the time from the source event to analog capture in He-3, the cell in which the capture occurred and the source particle number of a given history. Each row represents a single neutron capture event in the He-3 detector, thus the number of rows in the PTRAC file was equal to the total number of neutron events in the system. Binning these capture times in software enabled the capture time distribution for the detector to be generated. The die-away time was calculated to be 2.6 µs from a chi-squared minimisation fit to the data.

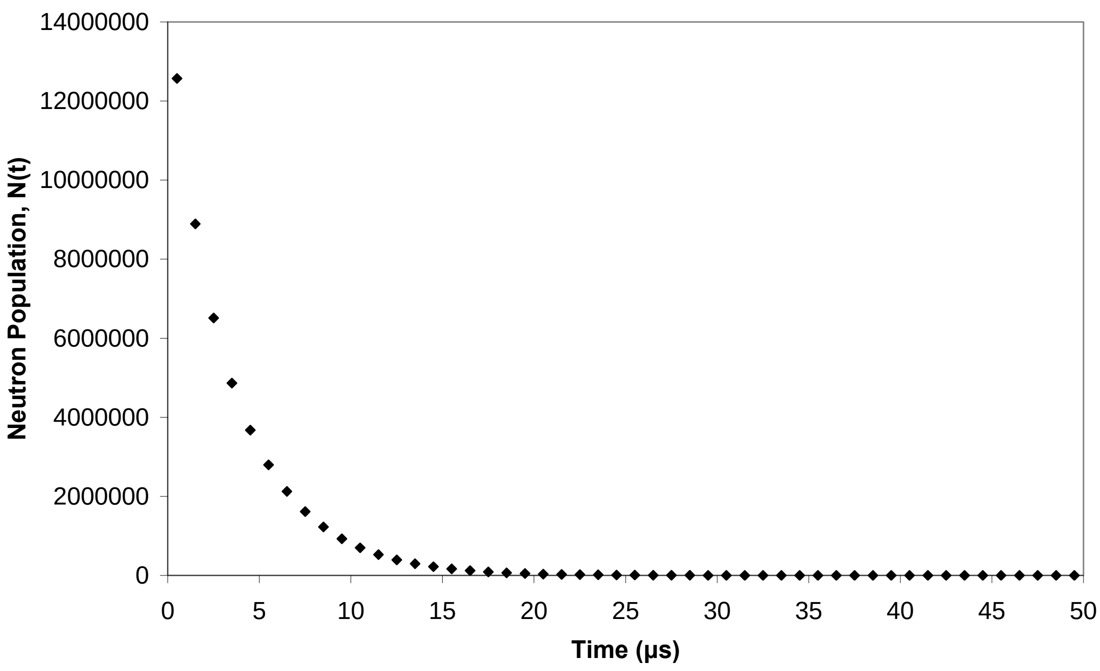

Fig. 1. Capture time distribution for an ideal (neutron detection efficiency, ε = 99.4%) He-3 detector modelled in MCNPX.

A NONU card was used to 'turn-off' induced fissions within the source material. This meant that the resulting pulse train consisted of neutron events from spontaneous fission only which is a fair approximation for actual Cf-252 sources.

Neutron Pulse Train Generation: Software (C++)

The MCNPX calculation is time-independent therefore all source fission events occur at time t=0. The PTRAC file was read into software in order to distribute the time between source fission events according to the well known interval distribution [8]. This was achieved by generating random numbers between 0 and 1 and multiplying them by the experimental time to generate a list of absolute start times of each fission event. The start time of each fission event was then added to the capture times of all neutrons originating from that fission event resulting in a random distribution of correlated neutron captures. The data was time sorted using a standard sort algorithm in C++ in order to produce a time-ordered neutron pulse train as in a real system.

Each pulse train was stored within a data structure. This allowed information on the location of the capture event in the system geometry to be retained for future work. Knowing which detector individual neutrons were captured in would be useful for future studies into dead-time effects from single and multiple input channels i.e. serial vs parallel processing of the detected pulse trains at the MSR.

Simulation of MSR Action in Software (C++)

The action of the MSR was simulated in software using C++. In the reported simulations each neutron event within the pulse train acts as a trigger particle and opens a coincidence gate of width 64 μs following a 4.5 μs pre-delay. A delayed accidentals gate of width 64 μs is opened following a long delay period of 4096 μs. Every neutron event in the pulse train was compared to the trigger event in order to build up a histogram describing the frequency of the observed multiplicities of events occurring within the gate width. The choice of parameters is purely nominal for illustration but is fairly typical of MSR commonly encountered. The optimum gate width for the die-away profile illustrated in Figure 1 would be shorter (at high counting rates) while in real life the pre-delay would be dependent on the transients of the electronics, which for modern implementation may well be in the sub 2 μs range.

The number of events falling within the first coincidence gate is tallied in a counter. The counter total is transferred to the R + A scalers at the time of the next trigger particle to build up a histogram of events. The accidentals gate totals are transferred to the A scalers in the same manner.

Calculation of Count Rates from the MSR Histograms

The measured Singles, Doubles and Triples count rates uncorrected for dead-time were calculated from the multiplicity histograms. The measured Singles rate S_m is the sum of all trigger events, calculated by the sum over all elements of the raw Accidentals histogram A_i divided by the experimental count time t given by the following:

$$S_m = \frac{1}{t}\sum_{i=0}^{255} A_i \qquad \text{(Eq.1)}$$

The measured Doubles rate D_m is given by the first factorial moment of the difference between the R+A and A histograms:

$$D_m = \frac{1}{t}\sum_{i=1}^{255} i \cdot \left[(R+A)_i - A_i\right] \qquad \text{(Eq. 2)}$$

The measured Triples rate T_m is given by the second factorial moment:

$$T_m = \frac{1}{t}\sum_{i=2}^{255} \frac{i \cdot (i-1)}{2}\left[(R+A)_i - A_i\right] - S_m \cdot D_m \cdot T_g \qquad \text{(Eq.3)}$$

The experimental count time t in each case represents the time between the first and final trigger events in the simulated MSR. The final trigger event is calculated to be at least (4096 + 64)µs from the last event in the pulse train to allow a complete evaluation of the A gate.

Building Dead-Time Effects into the Code

The ideal time ordered pulse trains were subjected to different dead-time effects within the MSR code. If the time of a pulse occurred during the specified dead-time of a preceding pulse this event would be rejected. In the non-paralyzable case, no further processing would be carried out with this event time. In the paralyzable case, the dead-time imposed by this pulse would extend the dead-time of the previous pulse.

RESULTS OF SIMULATION

Results are presented here for the initial work on the simulation method. Results are shown for Cf-252 modelled with a source intensity of 100 kHz and an experimental count time of 187.85 s. This count time corresponds to a total of 5 x 10^6 fission events modelled in the MCNPX input file.

Figure 2 shows the variation of the measured uncorrected Singles, Doubles and Triples count rates against dead-time parameter using the paralyzable model of dead-time. Dead-time parameters are chosen over the range between zero dead-time and a dead-time parameter equal to the gate width of 64 μs. Figure 3 shows the result using the non-paralyzable model. Figures 4 and 5 were obtained using dead-time parameters over a smaller timescale – which is of more practical interest. Many neutron counting systems in the field have dead-times of the order of 1 μs although bespoke high performance multiplicity counters distribute the efficiency between many chains to reduce the dead-time to 100 ns or less.

It is possible to observe the decrease in the measured Singles, Doubles and Triples count rates with increasing dead-time parameter. The results show that the Singles, Doubles and Triples rates are increasingly affected by dead-time. Note that because the random Triples events depend on the square of the source strength the uncorrected rate can be driven negative. Although a negative rate does not have physical meaning, this highlights the large effect of dead-time on the higher order rates and the importance of deriving accurate correction factors for these effects.

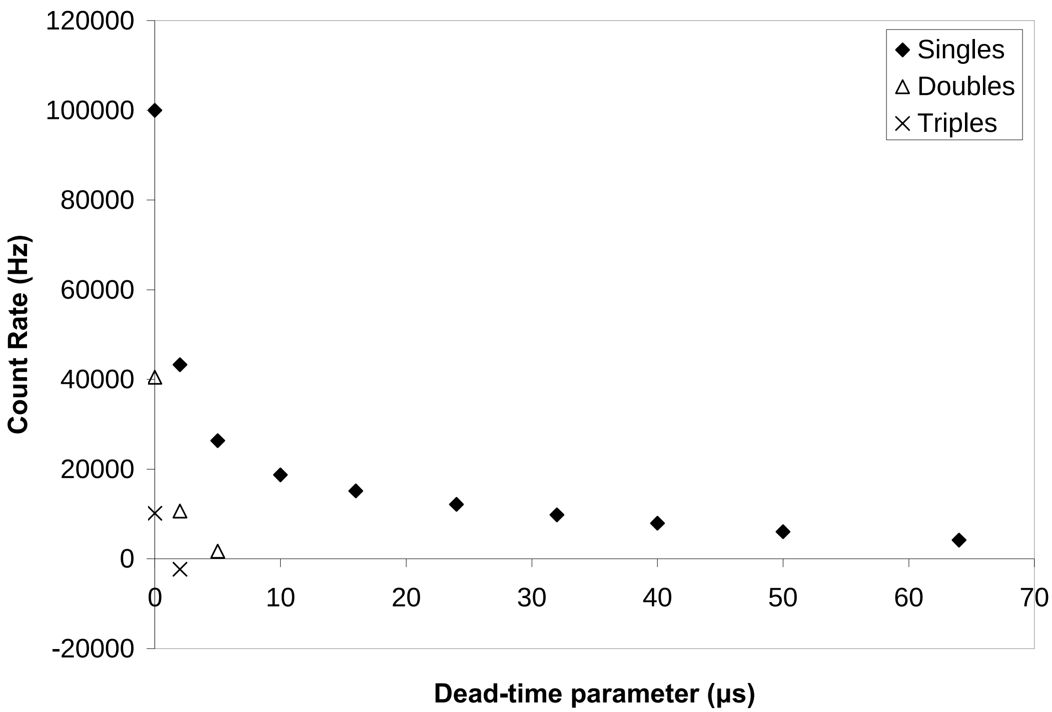

Fig. 2. Variation of the measured, uncorrected S, D and T rates against system dead-time parameter using the paralyzable model of dead-time

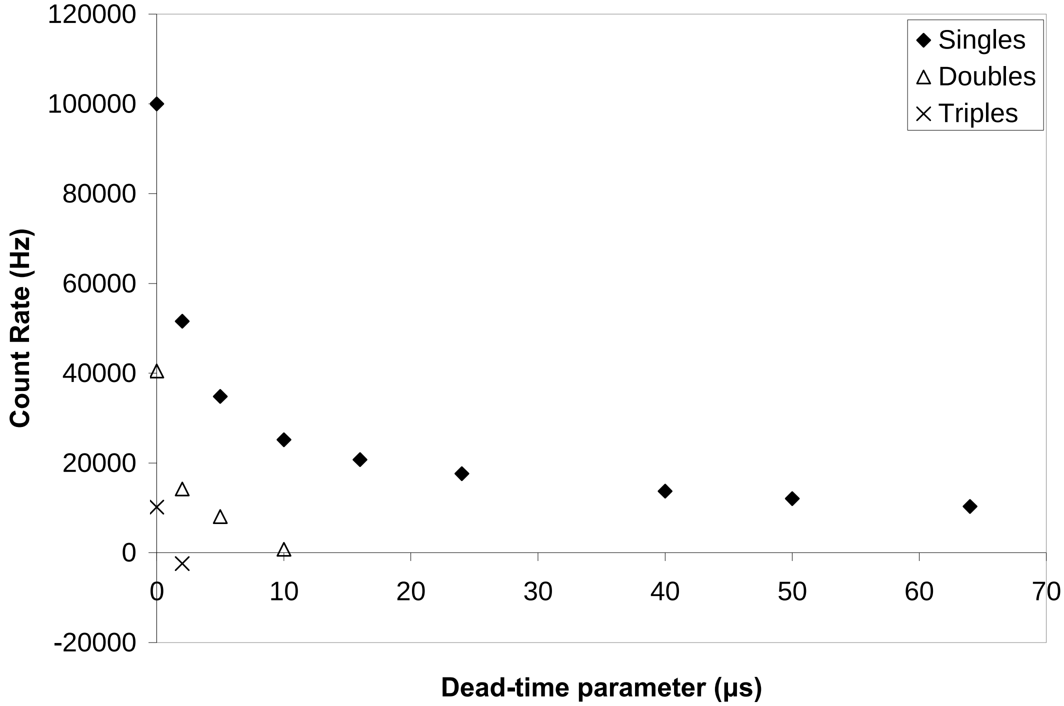

Fig. 3. Variation of the measured, uncorrected S, D and T rates against system dead-time parameter using the non-paralyzable model of dead-time

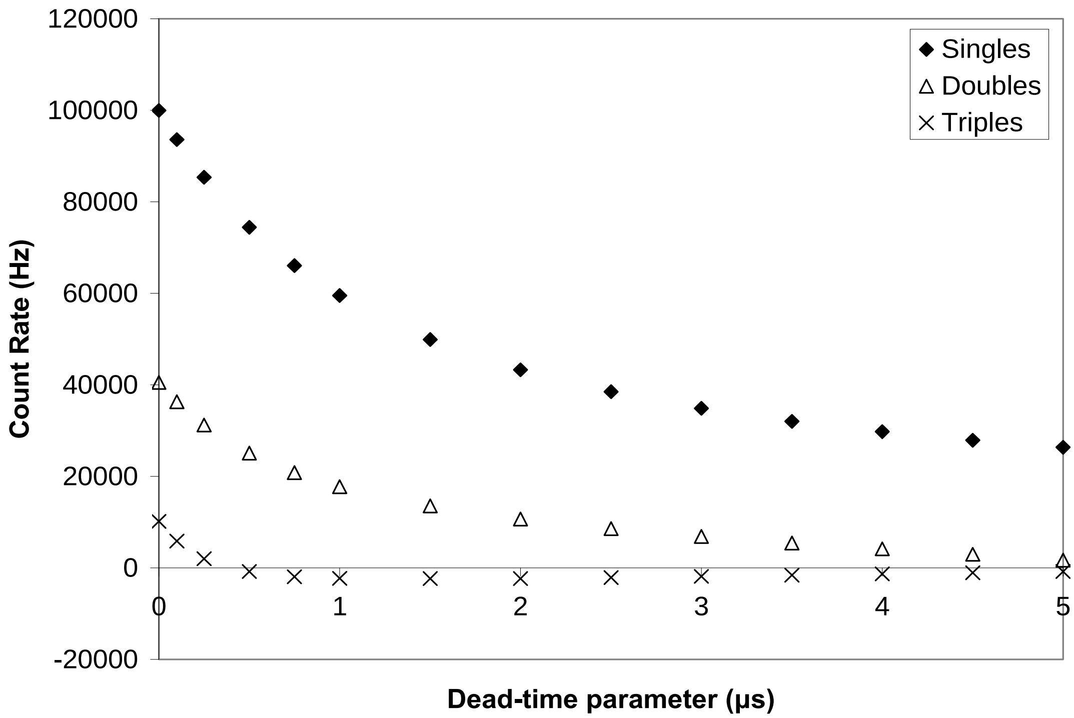

Fig. 4. Variation of the measured, uncorrected S, D and T rates against system dead-time parameter using the paralyzable model of dead-time, for small values of dead-time parameter

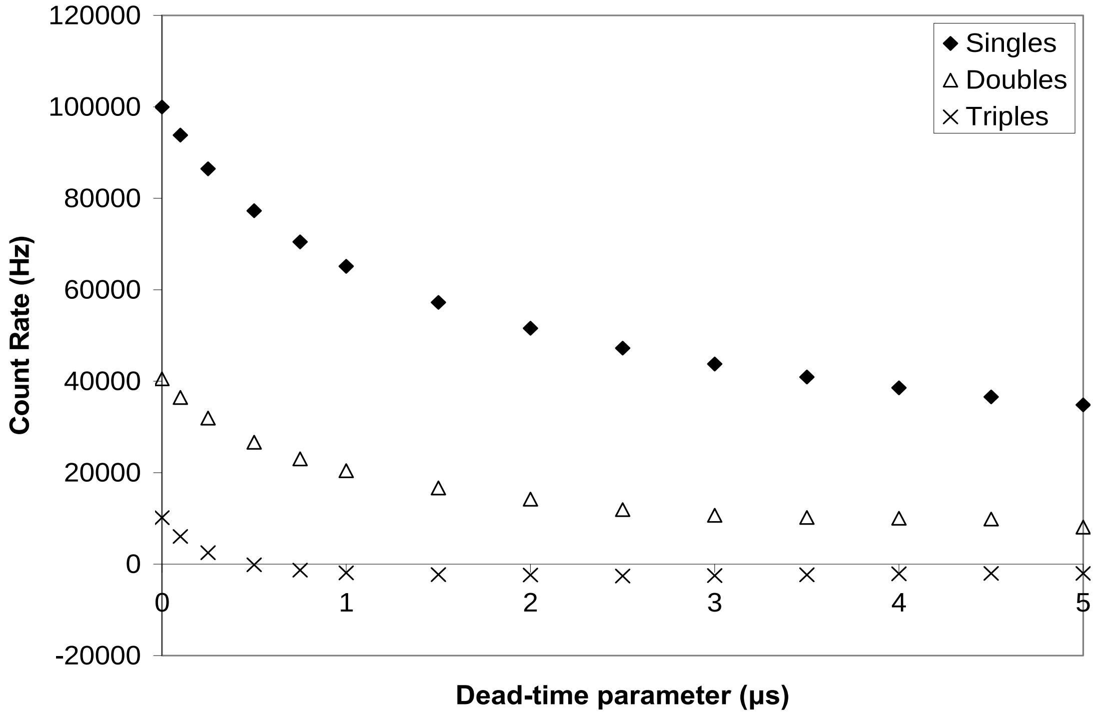

Fig. 5. Variation of the measured, uncorrected S, D and T rates against system dead-time parameter using the non-paralyzable model of dead-time, for small values of dead-time parameter

Figure 6 shows the combination of the data from figures 4 and 5. From this plot it is possible to directly compare the effect of the two models of dead-time on the Singles, Doubles and Triples rates. The measured rates obtained as a result of applying the paralyzable model of dead-time decrease more rapidly than the rates obtained using the non-paralyzable model.

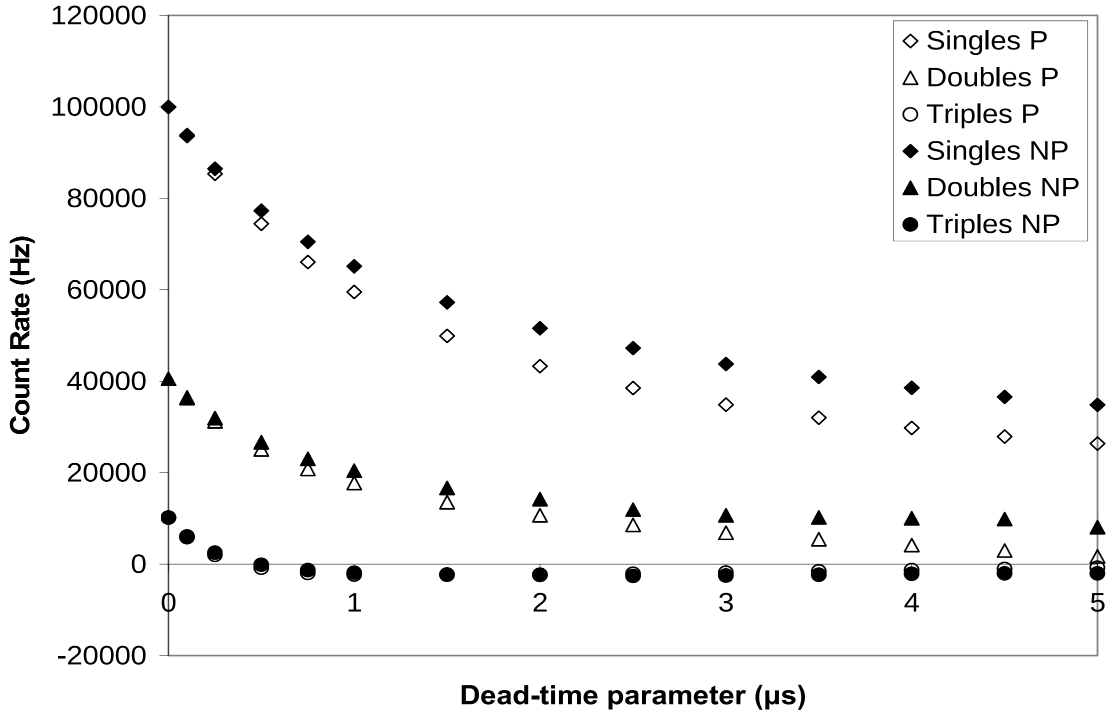

Fig. 6. Comparison of the Variation of the measured, uncorrected S, D and T rates against system dead-time parameter using both the non-paralyzable and paralyzable models of dead-time, for small values of dead-time parameter

CONCLUSIONS

Once established, simulation of the neutron pulse train and the action of the MSR in software provides a useful tool for conducting a systematic study of dead-time effects in PNMC counting systems. It is possible to observe the change in the measured Singles, Doubles and Triples rates over a range of dead-time parameters and to directly compare different models of dead-time.

FUTURE WORK

Plenty of research remains to be carried out in relation to the application of dead-time corrections to multiplicity counting. The method of simulation established will be used to support future work into the re-evaluation of dead-time correction methodologies. A statistical analysis will be added based on splitting the pulse train into segments to mimic replicate counting of an item. It is hoped to be able to use the simulation to study dead-time behaviour over a wide range of operational conditions such as the variation of efficiency, the ratio of correlated to non-correlated sources (increasing the random background contribution due to the (α, n) rate), for various types of real assay systems. Dead-time behaviour will also be modelled for the inclusion of single/ multiple detector boards within the counting system. Further to this, different dead-time models, including hybrids, could be applied at different stages of the simulation.

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