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Correction of dead-time and pile-up in a detector array for constant and rapidly varying counting rates

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ABSTRACT

The effect of dead-time and pile-up in counting experiments may become a significant source of uncertainty if not properly taken into account. Although analytical solutions to this problem have been proposed for simple set-ups with one or two detectors, these are limited when it comes to arrays where time correlation between the detector modules is used, and also in situations of variable counting rates. In this paper we describe the dead-time and pile-up corrections applied to the n_TOF Total Absorption Calorimeter (TAC), a 4π γ-ray detector made of 40 BaF_2 modules operating at the CERN n_TOF facility. Our method is based on the simulation of the complete signal detection and event reconstruction processes and can be applied as well in the case of rapidly varying counting rates. The method is discussed in detail and then we present its successful application to the particular case of the measurement of $^{238}U(n,\gamma)$ reactions with the TAC detector.

1. Introduction and motivation

Detector arrays are employed in many fields for the detection of multi-particle events, in particular in γ-ray detection and spectroscopy. In these experiments, the requirement of a time coincidence between the modules of an array provides event acceptance criteria and background discrimination capabilities. For instance, time coincidence between a charged particle and a γ-ray detector can be used to select only β-decay [1] or fission [2] events amongst all the detected events, while the so-called anti-coincidence condition between modules serves to identify and eliminate background events, as it is done with anti-Compton auxiliary detectors [3,4]. Last, the information from several detectors in coincidence can be used to select events fulfilling some particular conditions on the event characteristics: its energy, directionality, multiplicity, and so on.

In the simple case of one or two detectors operating in coincidence there are hardware and analytical solutions [5–9] for correcting the effect of dead-time and pile-up. However, many experiments in nuclear physics use large arrays of many detectors for which such analytical corrections are not easy or are even impossible to implement, due to the increasing complexity of the event reconstruction.

In this work we discuss the problem and the solution proposed for correcting the dead-time and pile-up effects in the case of the Total Absorption Calorimeter (TAC) [10], a 4π γ-ray detector made of 40 BaF_2 modules operating at the CERN neutron time-of-flight facility n_TOF [11]. At n_TOF these 40 BaF_2 scintillators are operated in coincidence to detect the γ-ray cascades that follow the neutron capture reactions of interest. These reactions are measured as a function of the time-of-flight of the incident pulsed neutron beam and, because the associated reaction cross-section features strong resonances, the counting rates achieved are rapidly variable, reaching peaks of up to several reactions per microsecond.

Most of the scintillation light from BaF_2 is emitted with a decay constant of 630 ns and thus in high counting rate experiments there is a sizable probability of signal pile-up. In addition, there is a non-negligible probability of two consecutive events falling inside the coincidence window. On top of this, in the particular case that we present in this paper, an event is only considered as such when fulfilling some conditions on the total energy deposited in all the BaF_2 modules and on the event multiplicity, thus the loss of a signal in one or more modules of the array may not only reduce the number of detected events but modify as well the observed response of the detector to multi-particle events in terms of energy and multiplicity. All these characteristics make dead-time and pile-up

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corrections important but quite difficult to quantify in the TAC measurements. Therefore we have developed a new method that is based on Monte Carlo simulations and mimics the full process of signal detection and event reconstruction, and allows investigating these effects even in the case of rapidly varying counting rates.

In principle, the new method presented herein can be applied to any counting experiment where the data are stored in so-called list-mode, so that the coincidence between the different detectors in the array is performed off-line by software. With the additional help of a Monte Carlo simulation for the generation of events, the method is also applicable to experiments where the coincidence is performed by hardware and thus there are no data available from the individual detectors.

The details about the TAC and the associated pile-up and dead-time effects on the individual crystal and the detector operating as a whole are presented in Section 2. Then the method for calculating and correcting for dead-time and pile-up effects is described in Section 3, where the method is applied and validated for a TAC measurement of $^{238}U(n,\gamma)$ reactions. The end of the section includes some comments on the accuracy and limitations of the method.

2. The case of the TAC detector array

The n_TOF Total Absorption Calorimeter (TAC) [10] is a representative example of a highly segmented detector in which analysis conditions in two parameters describing the detected events, total energy (E) and multiplicity (m_{cr}), are used to identify different types of reactions and optimize the signal-to-background ratio. In the following there is a brief description of the experimental set-up, followed by the characterization of the dead-time and pile-up in the TAC. The implementation of the proposed method to the TAC is discussed in Section 3.

2.1. Description of the TAC

At the CERN n_TOF facility [11] neutron capture cross-sections are measured using the time-of-flight technique. A pulsed neutron beam travels a flight path distance of $L = 185$ m before reaching the sample of interest, producing (n,γ) reactions at the time t_{tof}. Then the energy E_n of the neutron inducing the reaction is calculated, in the non-relativistic approximation, as $E_n = m_n/2(L/t_{tof})^2$.

The electromagnetic cascades of several γ-rays following each (n,γ) reaction are detected using the TAC, a 4π array made of 40 BaF_2 crystal modules forming a hollow sphere with 10 cm and 25 cm inner and outer radius, respectively. The signals from each module are digitized using Acqiris flash-ADC with 8 MB memory sampling at 250 M Samples/s [12], resulting in an event dead-time free acquisition system. The digitized data buffers are analyzed off-line [13] and the information of signal energy and t_{tof} in each module is stored in list-mode. In the next step the information from all the modules are combined applying coincidence windows of $\tau_{coinc} \sim 20$ ns. The result is a list of events characterized by the detection time t_{tof}, the total energy deposited E, and the number of BaF_2 modules m_{cr} involved in the detection of the event. The energy and multiplicity of the recorded events are related to the nature of the measured reaction and thus applying analysis conditions on these variables helps improving the capture-to-background ratio. Full details of the detector's use for neutron capture experiments are given in Refs. [14–16].

2.2. Signal dead-time and pile-up in BaF_2

The signal pile-up and dead-time losses in the TAC appear due to the existence of a slow component in the light emission in BaF_2. Although a fraction of the scintillation light produced in BaF_2 scintillators is emitted following an exponential decay of only $\tau_{fast}=0.7$ ns, which is responsible for the good timing properties of BaF_2, the rest is emitted following a slower decay of $\tau_{slow}=630$ ns, resulting in a non-negligible probability that a signal is sitting on the tail of a previous one and hence making the identification by the Pulse Shape Analysis (PSA) software [13] difficult. The type of signals and pile-up that we are discussing is illustrated in Fig. 1, which shows a set of five consecutive signals recorded in a single BaF_2 module within less than 8 μs. The solid lines correspond to the signals as identified and reconstructed by the PSA software.

The signal dead-time τ_{dt} of the individual BaF_2 modules has been determined experimentally as a function of the signal energies from the time interval distribution between consecutive signals when measuring at a constant counting rate ($\sim 1\ \mu s^{-1}$ in this case). Some of these distributions are displayed in the left panel of Fig. 2. It is observed that the expected exponential behavior is followed only for time intervals longer than a limiting value that is identified as τ_{dt}. Furthermore, it is observed that τ_{dt} has a dependence with the energies E_1 and E_2 of the two consecutive signals, thus becoming $\tau_{dt}(E_1, E_2)$.

We define the dead-time value for a given time interval distribution for a selected pair of energies as the shortest time for which the recorded distribution differs less than 10% from the expected exponential behavior. This value $\tau_{dt}(E_1, E_2)$ has been determined for all combinations of E_1 and E_2 in small energy intervals of 500 keV up to 6.5 MeV. The resulting two dimensional distribution is displayed in the right panel of Fig. 2. It features an average value of $\overline{\tau_{dt}} \sim 1$ μs, with values decreasing with E_2 and increasing with E_1 up to a maximum of 3 μs (five times the decay constant τ_{slow} of the slow scintillation component in BaF_2).

Regarding the signal pile-up, we have taken advantage of the fact that we store all the digitized signals from the measurement and have created artificial data buffers from individual digitized signals of known energy, looking at the result of analyzing these data buffers as a function of the energy of the two signals involved and the time distance between them. Doing this with millions of signals and their combinations we have estimated not only the probability of one signal killing another one (signal dead-time) as a function of their energies and time distance, but also the variation in the energy assigned to one signal when the other one is not detected (signal pile-up). Full details are given in Ref. [17].

2.3. Pile-up and dead-time in the TAC

As mentioned before, the events detected in the TAC are only considered valid if they fulfill some conditions on total energy (E) and multiplicity (m_{cr}). Therefore the loss of just one signal of the event in a given module may or may not result in the loss of the

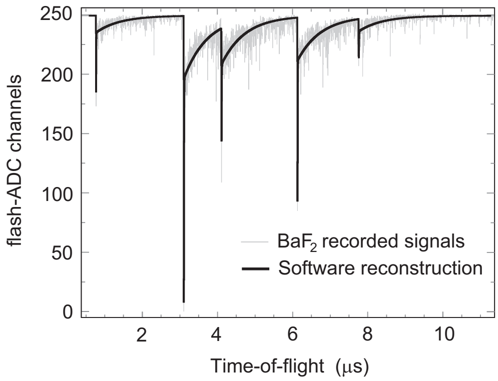

Fig. 1. Digitized buffer containing five signals recorded in a single BaF_2 module within only 8 μs. The solid lines correspond to the signals as identified and reconstructed by the Pulse Shape Analysis (PSA) software [13].