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Pulse pile-up identification and reconstruction for liquid scintillator based neutron detectors

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ABSTRACT

The issue of pulse pile-up is frequently encountered in nuclear experiments involving high counting rates, which will distort the pulse shapes and the energy spectra. A digital method of off-line processing of pile-up pulses is presented. The pile-up pulses were firstly identified by detecting the downward-going zero-crossings in the first-order derivative of the original signal, and then the constituent pulses were reconstructed based on comparing the pile-up pulse with four models that are generated by combining pairs of neutron and γ standard pulses together with a controllable time interval. The accuracy of this method in resolving the pile-up events was investigated as a function of the time interval between two pulses constituting a pile-up event. The obtained results show that the method is capable of disentangling two pulses with a time interval among them down to 20 ns, as well as classifying them as neutrons or γ rays. Furthermore, the error of reconstructing pile-up pulses could be kept below 6% when successive peaks were separated by more than 50 ns. By applying the method in a high counting rate of pile-up events measurement of the NEutron Detector Array (NEDA), it was empirically found that this method can reconstruct the pile-up pulses and perform neutron-γ discrimination quite accurately. It can also significantly correct the distorted pulse height spectrum due to pile-up events.

1. Introduction

High counting rates in radiation detectors is a common fact in nuclear spectroscopy as well as in nuclear reaction studies. For such applications involving high counting rates, the pile-up effect, in which more than one event occur simultaneously or closely spaced in time, becomes a severe issue. It results in two or more recorded signals partially or even completely overlapping, thus leading to a decrease in the counting efficiency, distortion of the pulse shape, and deterioration in the energy resolution.

Typically, pile-up events are diminished by reducing the pulse width with shaping networks, at the expense of a poorer performance in

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terms of signal-to-noise ratio. Since compressing signal pulses can only reduce the probability of the occurrence of pile-up but cannot totally eliminate it, hardware-based pile-up rejectors are often employed to identify the inevitable pile-up events and then discard them [1–4]. Although rejectors of this type can reduce the spectral distortions arising from pile-up to some extent, they negatively impact on the system throughput. Furthermore, some recorded events correspond to the pile-up of pulses that almost completely overlap, so that the recorded amplitude distribution is still distorted compared with the true event spectrum.

With the availability of digital signal processing techniques, digital treatments of pile-up have been introduced and adopted which yield significant advantages over conventional analog approaches. However, these are typically quite complex and not yet routinely employed in standard spectroscopy systems in which the pulse analysis is carried out in real time. The digital methods offer the possibility of preserving and analyzing in detail all the information carried by the overlapping pulses rather than simply rejecting them and tolerating the losses due to pile-up [5]. Various developed algorithms, such as the fitting method [6,7] and the deconvolution method [8], have successfully disentangled pile-up pulses with good accuracy, provided that a minimum time interval of around 40–50 ns exists between the two successive pulses constituting a pile-up event. Not only these methods compensate for the counting losses and correct the spectral distortions resulting from pile-up, but they are also capable of recovering original information on the type and energy of the constituent particles of the pile-up events. However, most of the methods are somewhat limited by analytical and computational complexity. For instance, the fitting process of the pulse based on an exponential analytic model has to be performed by trial and error, as sometimes it is hard for the fitting to converge to the correct solution. In this study, the aim is to propose an easy-implemented and efficient method of pulse pile-up identification and reconstruction for signals from liquid scintillators similar to the type that are used by the neutron detector array NEDA [9–13]. The ongoing NEDA project addresses the physics of neutron-deficient as well as neutron-rich nuclei using both intense stable and radioactive ion beams. The full version of NEDA will consist of around 350 closely packed liquid scintillator detectors of type BC-501A, mainly in conjunction with large γ-ray arrays like AGATA [14,15]. For use in nuclear structure experiments, NEDA should have the capability to run at high counting rates, which leads to a significant fraction of pile-up events, while retaining a high neutron efficiency and an excellent neutron-gamma (n-γ) discrimination performance. In order to meet these requirements, the pile-up issue has to be dealt with appropriately in NEDA. Specifically, the idea is to identify pile-up pulses and then perform n-γ discrimination on an event-by-event basis by taking advantage of high speed signal sampling and digital signal processing. Therefore, data have been acquired with the experimental setup described in Section 2 to develop the approach of pile-up identification and reconstruction in NEDA. The principles and validation of the proposed approach are given and discussed in Section 3. The application of the approach in a high counting rate measurement is described in Section 4 and the conclusions in Section 5.

2. Experiment

Two experiments were carried out at Laboratori Nazionali di Legnaro. The first was performed in order to acquire large numbers of single neutron or γ ray pulses, which were later used to extract standard neutron- and γ-induced pulses, and to generate synthetic pile-up pulses, aiming at developing the approach of pile-up identification and reconstruction in Section 3. The second experiment was performed in order to acquire large numbers of real pile-up pulses, which were later used to further evaluate the proposed method as shown in Section 4.

The experimental setup is illustrated in Fig. 1. The first experiment is almost the same as that of our previous work [10] except that only a single photomultiplier tube (PMT) of type Hamamatsu R11833-100 was used in this measurement. This 8-stage, 5 in. diameter PMT, shielded with μ-metal from magnetic fields, was coupled to a cylindrical 5 inch by 5 inch detector cell containing liquid scintillator of type BC-501A. The high voltage was set to get a signal amplitude of about 1 V/MeV using a ^{60}Co source, which had an activity of about 2 MBq. A lead brick with a thickness of 5 cm was put between the source and the BC-501A detector to reduce the counting rate originating from γ rays without losing too many neutrons, thus keeping the counting rate of the PMT R11833-100 at around 2 kHz. A trigger and time reference detector consisting of a cylindrical 1 inch by 1 inch BaF_2 scintillator coupled to a 2 inch R2059 PMT was placed very close to the ^{252}Cf source for detection of γ rays. The threshold of the constant fraction discriminator (CFD) was set to approximately 30 keVee (keV electron equivalent). With the outputs of the two CFD units fed into the LeCroy 465 coincidence unit, a coincidence between the signals from the BC-501A and BaF_2 detectors was created, which was used as a trigger for the data acquisition system (GASIFIC) [16] and as a start signal for the time-to-amplitude converter (TAC). The counting rate of the BaF_2 detector was about 200 kHz and the coincidence rate was about 200 Hz. The TAC module was subsequently stopped by the delayed signal from the BaF_2 detector and measured the time-of-flight (TOF) difference between the detected γ rays and neutrons in the detectors. Signals from both detectors were digitized with a Struck SIS3350 digitiser [17] that has a 500 MHz sampling rate and 12-bit resolution (effective number of bits = 9.2). The analog TAC signals were digitized by a Struck SIS3302 digitiser working at a sampling rate of 100 MHz and with 16-bit resolution (effective number of bits ≈13).

In addition, a high count rate experiment was carried out by adding a pile-up selector block to the first experimental setup (Fig. 1). In this measurement, the lead brick was removed, and the distance between the BC-501A and the ^{252}Cf source was readjusted, which gave a count rate of 200 kHz in the BC-501A detector. Pile-up events are validated by a logic AND (see signal 3 on the right), from the coincidence of the NEDA CFD (signal 1) with the same signal delayed by 15 ns (to avoid self-triggering) and wide open 500 ns (signal 2). To have the system triggered by the first signal in the pile-up event, the CFD is further delayed with a gate delay generator module (signal 4) and sent to another AND module in coincidence with signal 3. The final trigger is then validated with a coincidence from the BaF_2. TOF is measured with a TAC module, started with the coincidence (signal 8) of the two detector CFDs (signals 6 and 7), triggered by the NEDA signal, and stopped with the BaF_2 signal delayed (signal 9). For the stop signal, a 170 ns delay cable was used in order to account for slow neutrons. As the logic signal is integrated through the cable, a leading-edge discriminator (LED) was used afterwards to restore its step shape. The trigger rate was about 200 Hz in this experiment. With this setup, pulses with intervals ranging from 10 ns to 500 ns were recorded.

In this study, the digital signals from the BC-501A detector, as well as the TOF information, were used for pile-up investigations.

3. Principles and validation of the approach

3.1. Preprocessing of the signals

The 500 MHz sampling rate and 12-bit resolution of the Struck SIS3350 digitiser allow detailed analysis and processing of the pulse waveforms from the BC-501A detector, originating from either neutrons or γ rays. Fig. 2 gives two examples of pile-up pulses after preprocessing, including CFD timing, baseline restoration and filtering. For each waveform, a range of 300 ns of the pulse was used for the analysis, as beyond this time span the first pulse has decayed to a negligible level [18], so that the occurrence of a second pulse does not constitute a pile-up event. The start time of the pulses constituting the pile-up event was determined by implementing a digital CFD. The CFD method firstly attenuated the original signal to 20% of the first peak amplitude, and then summed it with the delayed and inverted original signal. Finally, the point that this sum signal crosses the zero axis was extracted, which