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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.

Keywords: pile-up; digital; first-order derivative; neutron-γ discrimination; liquid scintillator.

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 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 [9-12]. 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 [13,14]. 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) [15] 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 digitised with a Struck SIS3350 digitiser [16] that has a 500 MHz sampling rate and 12-bit resolution (effective number of bits = 9.2). The analog TAC signals were digitised 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 170ns 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.

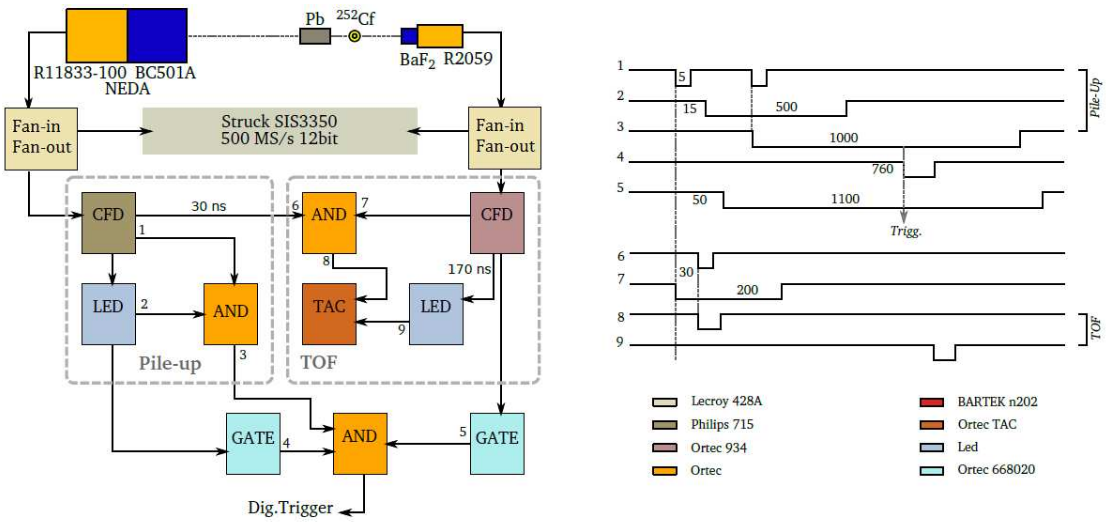

Fig. 1. Block scheme of the experimental setup (left) and the logic signals produced (right).

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 [17], 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 is independent of the pulse amplitude and corresponds to the time at which the original pulse reaches 20% of its first peak amplitude. It can be seen in Fig. 2 that after the CFD timing, the waveforms are well time aligned on the leading edge of the first peak. Moreover, the baseline shift has been eliminated from each pulse by subtracting the average value of the sampling points in the pre-trigger range of the waveform. A small amount of severely distorted pulses with heavily fluctuating baselines have been discarded (<1% of the total). In addition, a low-pass finite impulse response (FIR) digital filter has been applied to the pulses to remove high-frequency noise [18].

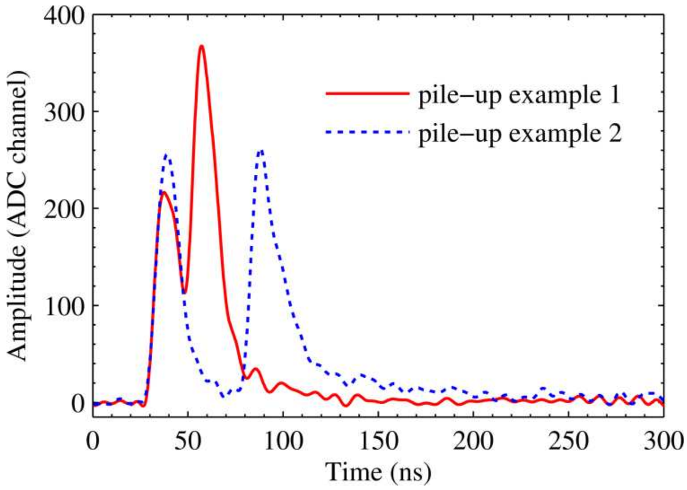

Fig. 2. Pile-up waveforms after the digital CFD time-aligning, baseline restoration, and filtering.

3.2. Pile-up pulse identification

When two or more peaks are detected within the duration of a recorded pulse (300 ns in the present work), a pile-up event is identified. The common way of detecting peaks is to search and find local maxima in the overlapping pulses, which may misidentify the spikes in the waveforms as pile-up events. In particular, the low energy signals are more likely to trigger false identifications because they are quite noisy due to the scintillation statistics, and to the electronic noise and the quantisation effects of the digitiser [19]. As shown in the upper plot of Fig. 3, the individual pulse will be misinterpreted as a pile-up event by the maximum peak search method, as more than two peaks can be detected. Therefore, another peak search method is proposed here. It is based on the fact that the first-order derivative is the slope of the original waveform and thus has a downward-going zero-crossing, which corresponds to the peak maximum of the original waveform. Since the presence of spikes in the original waveform will cause many false zero-crossings, the first-order derivative was smoothed using a moving-average filter prior to searching for downward-going zero-crossings [20]. Then, only those zero-crossings whose slope exceeds a certain threshold at a point where the original signal exceeds a certain amplitude threshold are counted. In this way the method detects only the desired peaks and ignores peaks that are too small, too wide, or too narrow, which are mostly random noises. If two or more peaks are detected in a signal, it is determined that a pile-up event has occurred. It should be noted that the position of the peak is not exactly equivalent to the position of the zero-crossing due to the fact that the smoothing can distort the waveform of the first-order derivative slightly. The position and height of each peak are determined by least-squares fitting of a segment of the original unsmoothed signal in the vicinity of the zero-crossing. Fig. 3 shows an individual pulse and its first-order derivative to illustrate the process of pile-up identification using the first-order derivative method, in which the only one true peak is correctly detected.

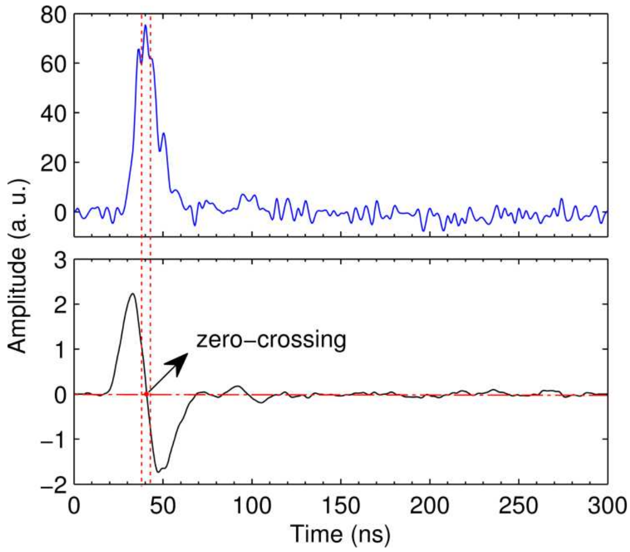

Fig. 3. An original waveform (upper panel) and its smoothed first-order derivative (lower panel).

3.3. Pile-up pulse reconstruction

Once a pile-up event is identified using the first-order derivative method described above, the next step is to resolve the overlapping pulses and reconstruct the individual constituent pulses. Most of the existing pile-up resolving methods process the first component and the second component of a pile-up event separately. The fitting method, for instance, firstly recovers the first constituent pulse of a pile-up event using a fitting procedure, and subsequently subtracts it from the original pile-up pulse to obtain the second constituent pulse. In contrast, the approach proposed in this paper treats the overlapping pulses that give rise to a pile-up event as a whole, which is the combination of a single neutron or γ pulse. In this way there are only four possible types of pile-up events under consideration, i.e. n+n, γ+γ, n+γ, γ+n, which means the combinations of the particle types of the first pulse and the second pulse. The main principle of the approach is to build four corresponding models by combining neutron and γ standard pulses with varying amplitude and time spacing, which are then used to compare with the pile-up pulse, and the model that has the highest degree of agreement with the pile-up pulse is determined as the type of the pile-up event. The neutron and γ-ray standard pulses were obtained by averaging a large number of neutron and γ-ray pulses respectively, which were extracted from n-γ discrimination results of both the digital Charge Comparison (CC) [21] method and the TOF measurement, as illustrated in Fig. 4. Although the TOF measurement is very efficient to distinguish neutrons from γ rays, some misclassification cases still exist due to accidental coincidences and to the emission of delayed γ rays from the spontaneous fission of ^{252}Cf. Therefore, the digital CC pulse shape discrimination (PSD) method, based on comparing the integrated charge over two different time periods of the pulse, was used to complement the TOF measurement to acquire as pure neutron and gamma-ray pulses as possible. The CC parameter in Fig. 4 represents the ratio between the tail integral and the total integral, of which the start points and end points have been optimised using the method of our previous work [10].

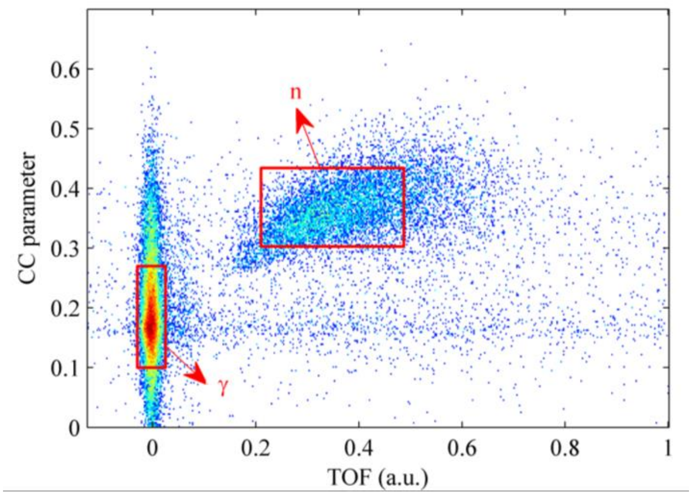

Fig. 4. Density plot of the n-γ discrimination parameter of the CC method versus the TOF of each pulse recorded by the experimental equipment.

Figure 5 shows the normalized standard neutron- and γ-induced pulses, as well as four pile-up models generated by adding pairs of standard pulses together separated by a time interval of 20 ns. It can be seen that the pulse shapes of the resulting pile-up models are quite distinguishable from each other, even though the constituent standard pulses have normalized amplitudes and the same time intervals. Thus, these differences in shape introduce the possibility of pile-up reconstruction based on the four pile-up models.

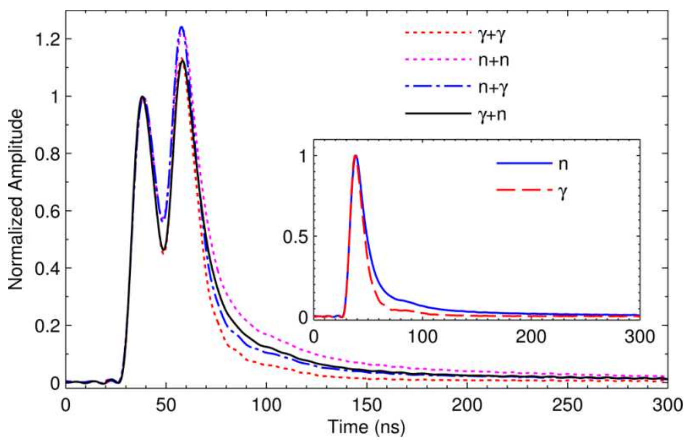

Fig. 5. Four pile-up models generated by adding pairs of neutron or γ standard pulses (shown in the inset), which are separated by a time interval of 20 ns.

For an observed pile-up pulse waveform, two parameters can be easily estimated from its shape, i. e. the amplitude ratio A_r and time intervals T_i between the second peak and the first peak. The four pile-up models are constructed continuously until their A_r and T_i agree with those of the pile-up pulse using an iterative algorithm proceeding as follows:

(1) The A_r and T_i of the detected pile-up pulse are obtained with the first-order derivative method described in section 3.2.

(2) The pile-up pulse is normalized to the amplitude of its first peak.

(3) A standard pulse (neutron or γ) is added with another standard pulse (neutron or γ) multiplied by $k=(0.7+n)\cdot A_r$ (the initial value of n is set to 0) with the temporal separation of T_i to form four types of models.

(4) For each model, the sum pulse is normalized to the amplitude of its first peak, and then the amplitude ratio between the second peak and the first peak $A_r^{'}$, which is the amplitude of the second peak after the normalization, is obtained.

(5) If $A_r^{'}$ is smaller/bigger than A_r, then n is increased/decreased by 0.001 and the process continues from step 3. If $A_r^{'}$ is equal to A_r, the iteration ends and the four models come to convergence.

Subsequently, the four models are evaluated point-by-point to the pile-up pulse that is normalized to the amplitude of its first peak respectively, and the model which has the minimum difference is determined as the type of the pile-up pulse (γ+γ/n+n/n+γ/γ+n). In order to evaluate the difference, the factors of "minimum absolute value of the sum of point differences", "minimum sum of absolute values of point differences", "minimum sum of quadratic point differences", and "minimum sum of quadratic relative point differences" were used respectively, it turned out that the method has the highest correct percentage when using the factor of "minimum absolute value of the sum of point differences". The reason is that this factor takes into account plus-minus differences, while other factors make all differences positive. While in this case, the factor is used to evaluate the degree of fitting between the model and the pile-up pulse, so it's better to include both negative and positive differences. Therefore, the "minimum absolute value of the sum of point differences" is chosen as the factor to compare between the pile-up pulse and the models. After the model type is determined, the original constituent pulses giving rise to the pile-up event are reconstructed as the first standard pulse multiplied by A_1 (amplitude of the first peak of the pile-up pulse) and the second standard pulse multiplied by $k\cdot A_1$.

For a proof of principle testing, synthetic pile-up data have been generated for four pile-up types respectively by randomly choosing pairs of single pulses of known types and adding them together with a controllable temporal separation, ranging from 20 ns to 60 ns in steps of 4 ns. The dataset for each case consisted of 10,000 synthesized pile-up pulses. The single pulses of known types were acquired by performing n-γ discrimination with the combination of the CC method and the TOF measurement as shown in Fig. 4, with no extra threshold other than the CFD hardware threshold of approximately 30 keVee. The dynamic range of these pulses, defined as the ratio between the maximum and minimum amplitude pulses, was found to be around 50. Four examples of the recovery of pile-up signals separated by 20 ns between two peaks are given in Fig. 6, which shows the normalized pile-up pulses, along with the corresponding models. It can be seen that the pile-up pulses all fit very well with the corresponding models both on a linear scale, as well as on a logarithmic scale shown in the insets. It is also clear from Fig. 6(a) that the other three models except the γ+γ model are distinct from the pile-up pulse in shape, mainly in the tail and the valley between the two peaks.

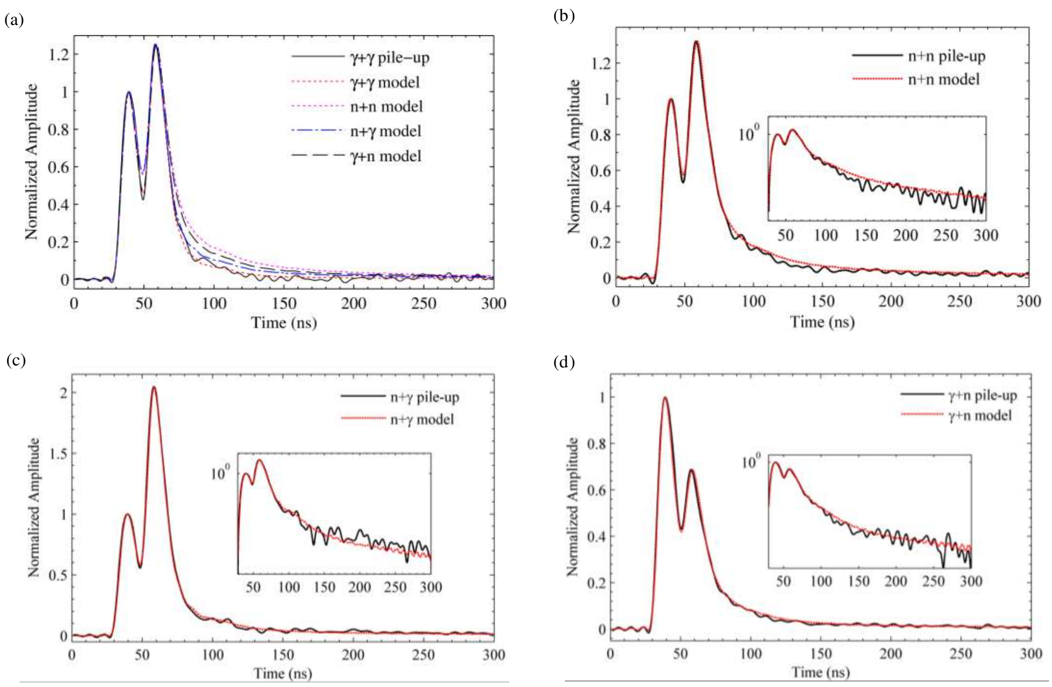

Fig. 6. Four types of pileup pulses which are separated by 20 ns and fitted with the corresponding models: (a) γ+γ, (b) n+n, (c) n+γ, and (d) γ+n.

Furthermore, the efficiency of the pile-up reconstruction method as a function of the time interval between two pulses constituting a pile-up event has been investigated using the synthetic pile-up data. Figure 7 illustrates the percentages of correctly reconstructed pile-up events for each type with varying time intervals between two constituent pulses, as well as the overall correct percentage for pile-up events comprising of same counts of pulses belonging to the four pile-up types, which is more realistic in practical nuclear experiments. It was found that a good performance in resolving pile-up events can be obtained from a time interval of 20 ns onwards. The overall correct percentage is around 90% with time intervals from 20 ns to 48 ns, while the error of reconstructing pile-up events can be kept below 6% when successive peaks are separated by more than 50 ns. It should be noted that this method almost failed to reconstruct pile-up pulses with time intervals below 20 ns, as the reconstructing accuracy deteriorated sharply from 20 ns downwards.

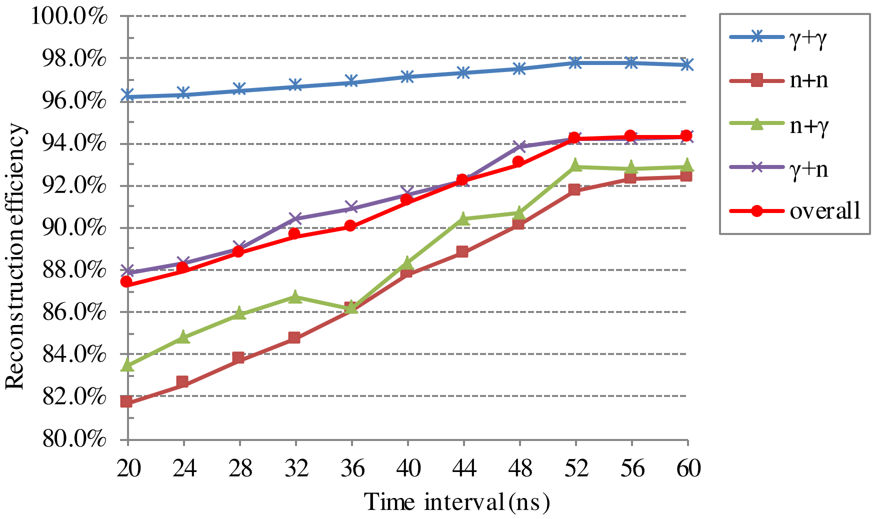

Fig. 7. The percentages of correctly reconstructed pile-up events versus the separation time between the two constituent pulses.

The results also indicate that the efficiency of the pile-up identification and reconstruction method depends on the type of pile-up pulses, and the time interval between the two constituent pulses. In general, the correctly reconstructed fractions of all types of the pile-up events improve as the time intervals increase. Meanwhile, the performance of the method varies among different types of pile-up events, while the type of γ+γ has the highest efficiency. This is reasonable as the pulse width of the standard γ-ray pulse is relatively narrow compared with that of the standard neutron pulse, thereby leading to less information lost in a pile-up pulse with a certain time interval between two peaks. For each case there are always some mistakenly reconstructed pile-up events that are caused by two reasons. One is the intrinsic limitation of the method when dealing with extreme cases, in which the pulse amplitude ratio is too large or the pulse temporal separation is too small. The other one is the type of pulses that are used for generating synthetic pile-up data sets can contain some misinterpreted neutron-gamma events, even though both the CC method and the TOF measurement were combined to discriminate them. Therefore, some correct reconstruction cases could be misclassified as wrong cases, as the pre-known types of the constituent pulses are in themselves wrong. However, the large percentages of correctly reconstructed pile-up events has demonstrated the effectiveness of this method, allowing it to be used for correcting the spectra distorted by pile-up events as shown in next section.

4. Application of the new method to NEDA data

In order to further evaluate the performance of the pulse pile-up identification and reconstruction method presented, it has been applied to the pile-up events from the high count-rate measurement described in Section 2.

By applying the approach of pulse pile-up identification and reconstruction to the experimental data, 66916 pile-up events have been detected in a total of 92239 events, which account for approximately 72.5% of the total events. It was empirically found that the method was able to locate the positions and to measure the amplitudes of the peaks in the pile-up events automatically and reconstruct them accurately, even though the peaks were randomly spaced in time and vary in amplitude. It should be noted that reconstruction processing here was restricted to the pile-up pulses arising from two events. Figure 8 shows an example of real pile-up identification and reconstruction. Despite the large pulse amplitude ratio between the two peaks, the result of resolving the pile-up event is quite satisfactory.

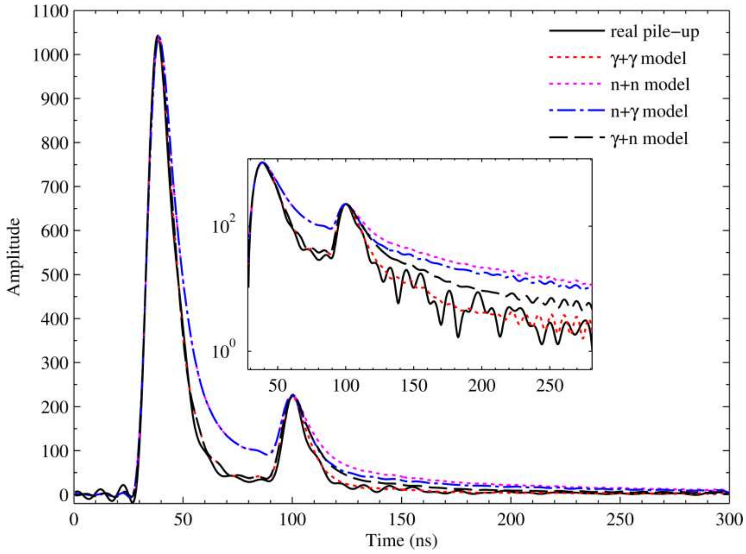

Fig. 8. A case of pile-up identification and reconstruction in the high counting rate measurement.

Rather than discarding the pile-up pulses, the new method can now allow them to be included in spectral analysis. Figure 9 shows the neutron pulse height spectra of ^{252}Cf before and after the pile-up correction, obtained by summing sampling points over the whole pulse width. Severe spectral distortions can be seen in the pulse height spectrum of the signals without pile-up correction. These distortions owing to pile-up events have been corrected significantly after applying the pulse pile-up identification and reconstruction method.

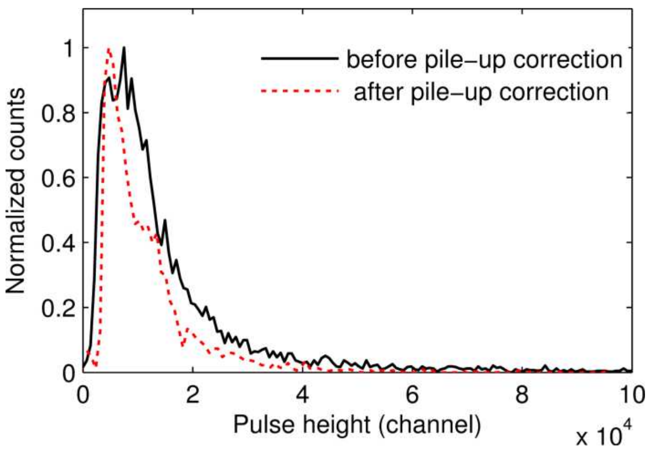

Fig. 9. The neutron pulse height spectra of ^{252}Cf before and after the pile-up correction (66916 pile-up events have been detected and reconstructed in a total of 92239 events).

5. Conclusions

A new method designed to deal with digital pulse pile-up identification and pulse reconstruction is presented in this paper. The digitised waveforms used for developing and validating the method were acquired with an experimental setup consisting of a ^{252}Cf source, a BC-501A detector and a SIS3530 digitiser with a sampling rate of 500 MHz and with 12-bit resolution. When identifying pile-up events by searching for the downward-going zero-crossings in the smoothed first-order derivative of the original pulse, the method was less vulnerable to fluctuations in the signal compared with the conventional maximum peak search method. Moreover, rather than discarding the detected pile-up pulses, as is the case in hardware-based pile-up rejectors, this method allows the reconstruction of the individual components of the pile-up events employing four models that are generated by combining pairs of neutron and γ standard pulses. Tests performed both on synthetic and experimental data demonstrated that the method was capable of recovering two overlapping signals with a high accuracy even when they are spaced in time as close as 20 ns. However, it should be noted that the method can only be applied to pile-up events where two pulses overlap. Since this method can provide reliable information of the constituent particles of the pile-up events, thus avoiding losses of counting statistics and distortions of pulse height spectra, it is of practical use to eliminate pulse pile-up effects on the neutron-gamma discrimination performance of liquid scintillator detectors used at high count rates.

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