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A hybrid pulse shape discrimination technique with enhanced performance at neutron energies below 500 keV

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ABSTRACT

A hybrid pulse shape discrimination (PSD) method is presented that combines a charge-integration PSD method with a reference-pulses PSD method. The reference-pulses PSD method uses detailed knowledge of the average, energy-dependent detector response to radiation. To obtain the reference-pulses, a large number of neutron and gamma-ray pulses was averaged in several pulse height regions. The reference neutron and gamma-ray pulses were then used in the new PSD method for the classification of a large number of measured pulses. The reference-pulses PSD method was applied below 70 keVee, whereas the standard charge-integration PSD method was used above 70 keVee. This new hybrid PSD method proves to be more accurate than the standard charge-integration PSD method for classification of neutrons and gamma rays. Specifically, the improvement is approximately 30% for neutrons in the smallest pulse height bin considered, which was between 20 and 30 keVee (corresponding to approximately 150 and 225 keV neutron energy deposited, respectively). For this pulse height bin, approximately 72% of the neutrons were correctly classified by the hybrid PSD method. The average number of correctly classified neutrons is approximately 88% for the hybrid PSD method between 20 and 100 keVee (corresponding to approximately 150 and 670 keV neutron energy deposited, respectively) as opposed to 83% for the charge-integration PSD method.

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1. Introduction

Neutron and gamma-ray pulse shape discrimination (PSD) using organic scintillation detectors is a widely adopted technique in fields such as nuclear nonproliferation, international safeguards, nuclear material control and accountability, and national security. In contrast to thermal neutron detectors such as ^{3}He tubes, organic scintillators are able to detect high-energy neutrons and do not need to use moderating material. These detectors are also sensitive to gamma rays, which makes them suitable for measurements in mixed neutron/gamma-ray fields. A large number of papers were published on the PSD performance of liquid scintillators [1–5]. In this paper, we present a new PSD approach that is based on detailed knowledge of the detector response to a given radiation. Specifically, an average detector response is obtained for several energies of interest, which is later used as a "reference" for particle identification. The main objective of this work is to further improve the current performance of the widely adopted charge-integration PSD method at neutron energies below 500 keV with commercially available measurement equipment. The reference-pulses PSD method is utilized at energies below 70 keVee (approximately 500 keV neutron energy deposited) while the charge-integration PSD method is used above 70 keVee. As a result, the "hybrid" PSD approach provides a higher level of accuracy at low energies when compared to the standard charge-integration approach.

2. Description of measurements

The measurements were performed using a CAEN V1720, 12 bit, 250 Mhz, 8-channel waveform digitizer. Neutron pulses were obtained using a 17 μCi (76,000 n/s) ^{252}Cf spontaneous-fission source, which was used in conjunction with two EJ-309 liquid scintillators as shown in Fig. 1.

The detector–detector distance was set to 40 cm. A time-of-flight (TOF) technique was utilized to obtain a large number of measured neutron pulses. These pulses were sorted out into eight pulse height bins and reference-pulses were computed by averaging the pulses in each bin. The pulse height bins range from 20 to 100 keVee (corresponding to approximately 150 and 670 keV deposited neutron energy, respectively). The structure of the bins is shown in Table 1. The TOF-attributed neutrons were used to test the performance of the PSD methods.

Known gamma-ray pulses were obtained using a single EJ-309 liquid scintillator and a ^{137}Cs source using the bin structure

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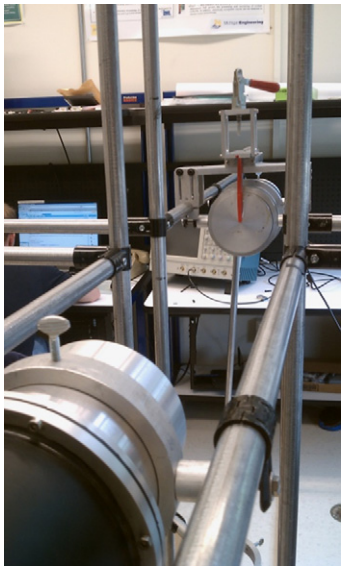

Fig. 1. The TOF experimental measurement setup, where the end of the red marker represents the location of the ^{252}Cf source used in the actual measurement. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 1
Description of light output bins. Values are shown for bin boundaries.

Bin number	Light output (keVee)	Neutron energy (keV)	TOF for 40 cm (ns)
1	20–30	150–225	61–75
2	30–40	225–295	53–61
3	40–50	295–362	48–53
4	50–60	362–427	44–48
5	60–70	427–490	41–44
6	70–80	490–552	39–41
7	80–90	552–611	37–39
8	90–100	611–670	35–37

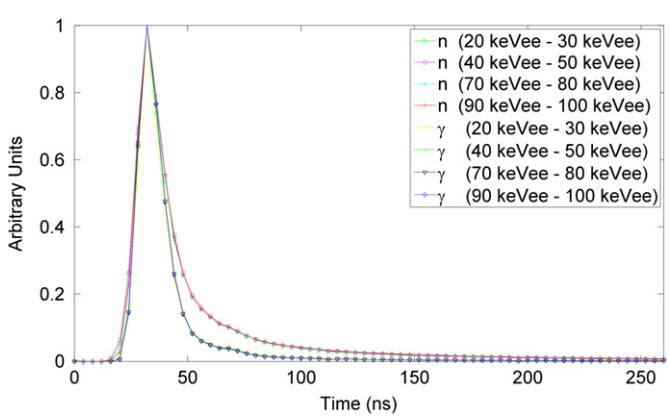

Fig. 2. Neutron and gamma-ray reference-pulses obtained by averaging many thousands of pulses in several pulse height bins (pulses normalized to unity).

described in Table 1. Fourteen thousand pulses were averaged in each pulse height bin to obtain reference gamma-ray pulses. Neutron pulses were obtained using the TOF method described in Section 4 and averaged to produce reference neutron pulses. These reference-pulses represent the typical detector response to both neutron and gamma rays. Some reference-pulses are shown in Fig. 2.

3. Description of TOF-attributed neutrons

In order to perform the TOF measurement we used the waveform digitizer described above. This digitizer typically stores waveforms from all active channels no matter which channel triggered. Therefore, signals from both detectors were stored each time a common trigger occurred. The obtained waveforms were then processed to calculate the TOF of each event. The number of accidentals was calculated by integrating the number of counts in the flat region (region between −60 and −100 ns) of the obtained TOF curve and dividing by the number of counts in the neutron region (between 20 and 60 ns). This resulted in an accidental fraction of approximately 1.4%.

The TOF region that was chosen for neutron identification/discrimination is shown in Fig. 3. The neutron region was chosen between 20 and 60 ns. The TOF-attributed neutron pulses were then binned by pulse height.

In this experiment, some of the TOF-attributed neutrons are in fact gamma rays due to accidental coincidences and to the emission of delayed gamma rays from the spontaneous fission of ^{252}Cf. The charge-integration PSD method was used to determine the approximate percentage of gamma-ray pulses in the neutron bins of interest. The optimized charge-integration PSD method provides excellent separation of neutron and gamma-ray pulses above 70 keVee. The percentages of gamma rays accidentally attributed as neutrons are shown in Fig. 4.

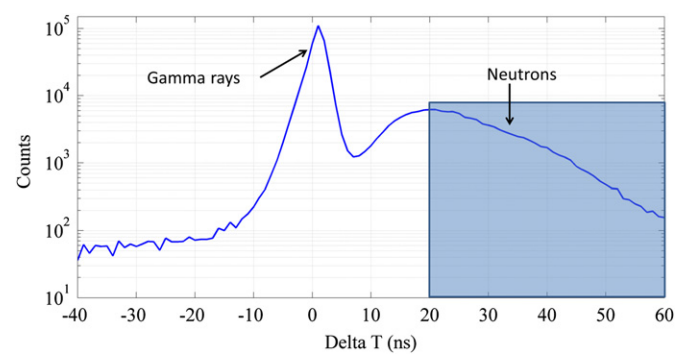

Fig. 3. Neutron and gamma-ray TOF spectrum measured with ^{252}Cf. The chosen neutron range is represented with the blue box. The neutron region starts at 20 ns and ends at 60 ns. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

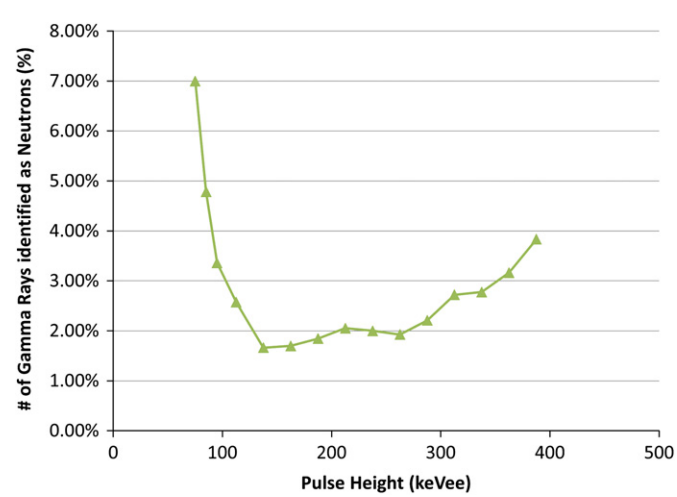

Fig. 4. The fraction of gamma-ray pulses identified as neutron pulses in the neutron TOF region as a function of pulse height. The investigation was performed above 70 keVee by using the charge-integration PSD method. Pulse height values represent the centers of the bins.

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It is shown in Fig. 4 that the number of misclassified gamma-ray pulses in the neutron TOF region increases exponentially with decreasing pulse height (energy) below 138 keVee. The source of the accidental gamma rays above the 1.4% flat background contribution mentioned above is likely from delayed gamma rays from the spontaneous fission.

4. Charge-integration method

An optimized charge-integration PSD method was used for light output bins above 70 keVee (500 keV neutron energy deposited). The threshold for the charge-integration PSD method was chosen based on extensive measurements done in the past [6]. Each pulse was integrated from the beginning of the pulse to an optimized end point in the tail. This integral is referred to as the total integral. The second integral was taken from an optimized starting position after the pulse maximum to the same end point as used for the total integral. This integral is referred to as the tail integral. Generally, the tail integral of a neutron pulse is larger than that of a gamma-ray pulse with the same pulse height. This is due to a larger portion of delayed scintillation light produced by heavier particles. In the scintillator, the gamma rays interact (produce light) through electrons while the neutrons interact through protons. Fig. 5 shows a typical PSD plot.

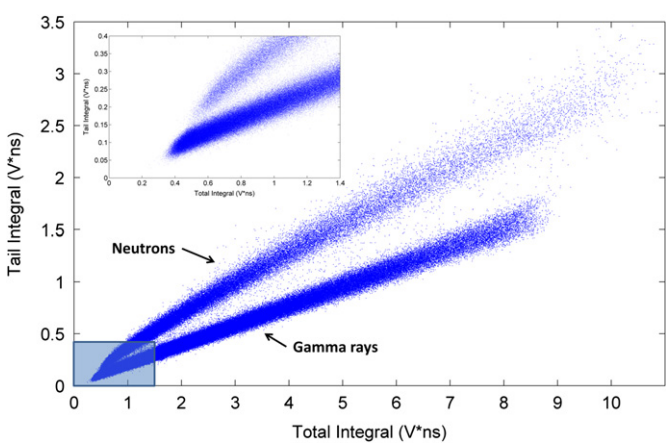

Fig. 5. Tail vs. total integral of measured pulses from a ^{252}Cf source with a threshold of 70 keVee.

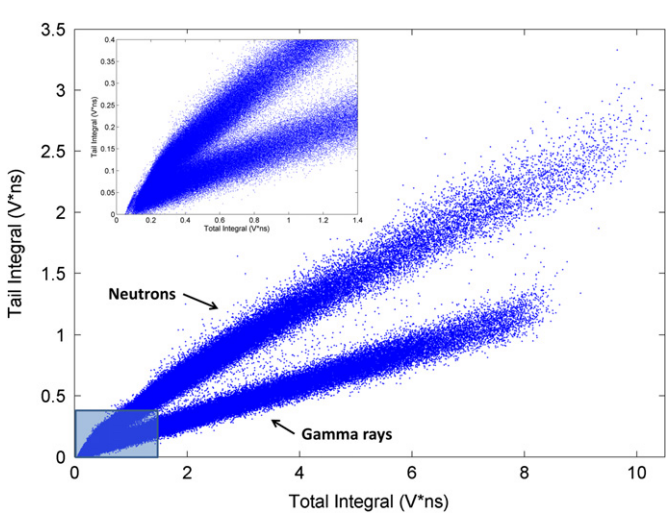

Fig. 6. Tail vs. total integral of measured pulses from a ^{252}Cf source with a threshold of 26 keVee.

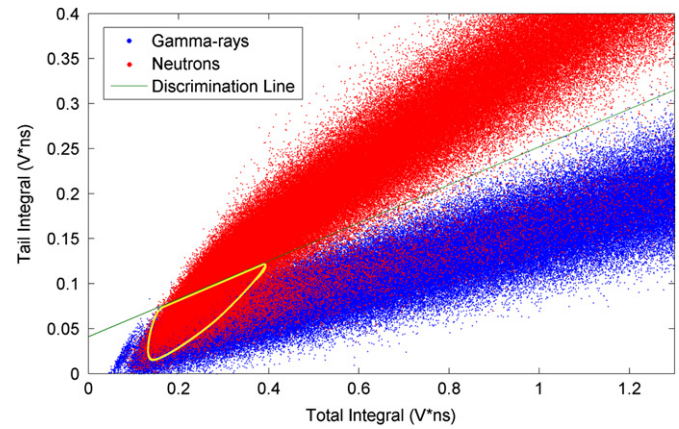

Fig. 7. Tail vs. total integral of measured pulses from a ^{252}Cf source. TOF-attributed neutron pulses (in red) and gamma-ray pulses (in blue) overlap (yellow boundary) at low energies when the charge-integration PSD method is used. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

It can be seen in Fig. 5 that the separation between neutrons and gamma rays is excellent above 70 keVee. A straight discrimination line can be used to separate the two regions. However, when the detection threshold is decreased to 26 keVee (200 keV neutron energy deposited) the separation becomes non-existent. This situation is shown in Fig. 6.

Due to the lack of separation the charge-integration method is unusable at low energies. To further explain this, the same plot as in Fig. 6 is shown in Fig. 7 with the TOF-attributed neutrons in red.

In Fig. 7, some additional neutron pulses are observed outside the yellow overlap region; these are accidentals (gamma rays; approximately 1.4% from the total number of the TOF-attributed neutrons) from the TOF measurement. The green line shows a straight discrimination line which is used to separate the neutron and gamma-ray pulses above 70 keVee.

5. Reference-pulses PSD

The fourteen thousand pulses per bin were averaged to obtain the reference-pulses for both neutron and gamma rays. The acquired average neutron and gamma-ray pulses were used as references for identifying and distinguishing neutrons from gamma rays measured with the EJ-309 scintillator. Specifically, each measured pulse was compared point-by-point in the appropriate pulse height bin to the reference neutron and gamma-ray pulses. The comparison was done from 16 ns after the pulse maximum to 488 ns after the pulse maximum; this is the optimized region that correctly identified most pulses. The reference-pulses and the "unknown" measured pulses were normalized to maximum in order to compare the pulse shapes regardless of the bin width. The absolute point differences were summed up in the tail region and the pulse was classified by the minimum value of the sums of differences and determined to be a neutron or gamma-ray. Fig. 8 shows an example of a measured neutron pulse and the reference-pulses.

The reference-pulses PSD method shows some improvement at low particle energies over the charge-integration method. The comparison results are shown in Fig. 9.

The reference-pulses PSD method shows increased classification accuracy below 70 keVee. This increase results in the improved performance of the hybrid PSD method that combines both the reference-pulses PSD method and the charge-integration PSD method.

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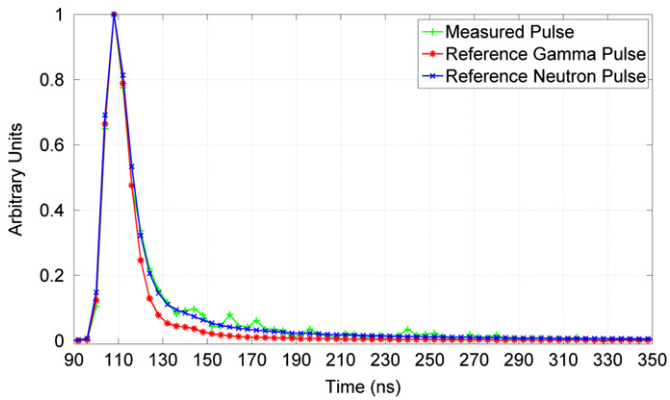

Fig. 8. Measured pulse and reference neutron and gamma-ray pulses. Bin #8 is shown. The measured pulse was correctly identified as a neutron.

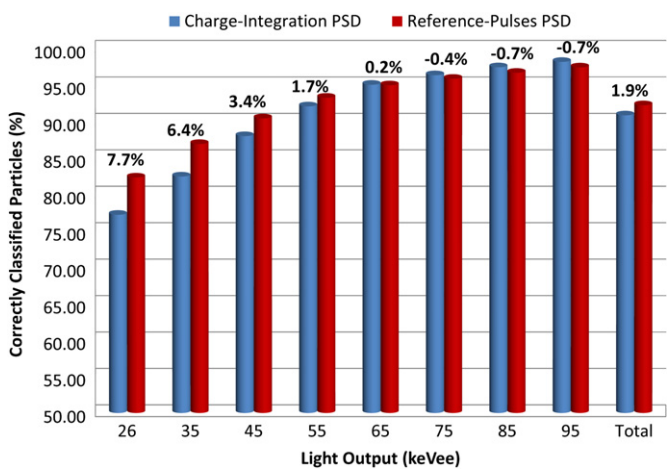

Fig. 9. Mixed-particle (50% of known neutrons and 50% of known gamma rays) classification using the reference-pulses and charge-integration PSD methods. Percentage values above the bars show the relative change compared to the charge-integration PSD.

6. Receiver operating characteristic (ROC) curves

ROC curves were used to characterize the performance of the reference-pulses PSD method and to find the best method for comparing the measured and average pulses. Seven comparison methods were chosen and compared and they are listed in Table 2.

The ROC curves were used to show how the fraction of false negatives changes as a function of the fraction of the energy window, i.e. a quantity related to the detection threshold. The false negatives are defined as particles that are classified incorrectly. In the case of Fig. 10 the false negatives are the fractions of gamma rays incorrectly classified as neutrons. As the fraction of light-output window increases the detection threshold decreases. The fraction equal to 1 represents the full light-output window from 20 to 100 keVee, while a fraction of 0.125 represents only bin 8, not bins 1–7. Fig. 10 shows the ROC curves for the 7 methods described in Table 2 for the ^{137}Cs gamma-ray pulses.

From Fig. 10 it is clear that methods 2 and 3 performed very well when identifying gamma rays. These methods had less than a 3% fraction of false negatives. Methods 4, 5, and 6 seem to over identify pulses as neutrons and therefore have a relatively high fraction of false negatives. In order to choose between methods 2 and 3 a ROC curve was made using neutrons to ensure that these methods also performed well at identifying neutrons.

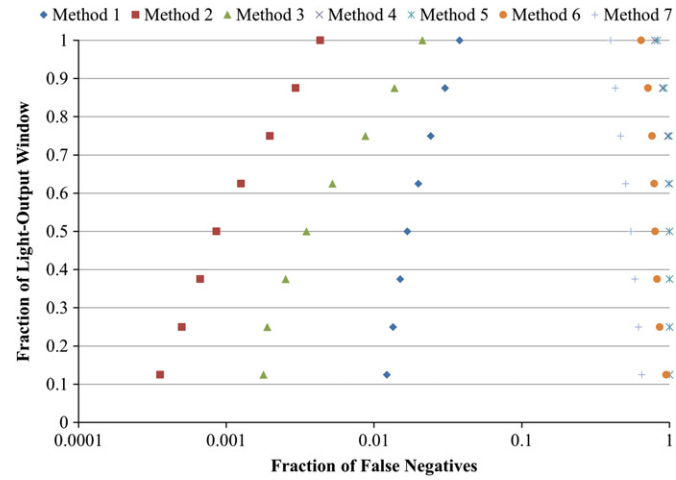

Fig. 10. ROC curves showing the change in the fraction of false negatives for the seven comparison methods described in Table 2 for gamma-ray pulses. The light-output window is 20–100 keVee and is divided into eight 10 keVee bins.

Table 2
Comparison methods.

Method number	Method description
1	Lowest sum of squared absolute errors
2	Lowest sum of absolute values of absolute errors
3	Lowest absolute value of the sum of absolute errors
4	Lowest sum of squared relative errors
5	Lowest sum of absolute values of relative errors
6	Lowest absolute value of the sum of relative errors
7	Lowest absolute value of 1 minus the mean chi squares

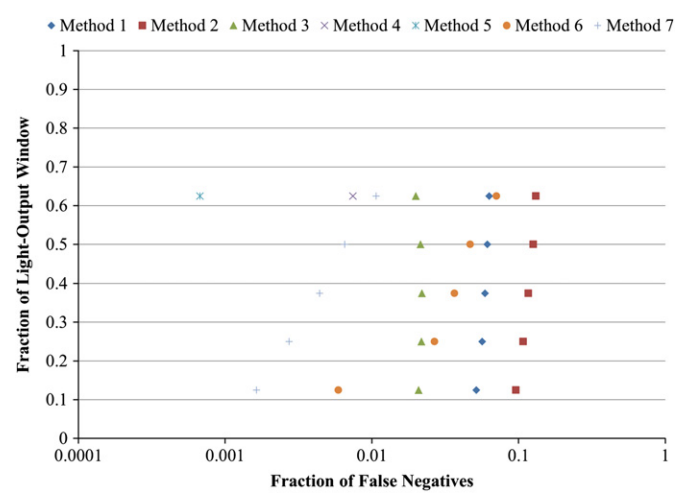

Fig. 11. ROC curves showing the change in the fraction of false negatives for the 7 comparison methods in Table 2 for cleaned neutron pulses. The energy window is from 50 to 100 keVee and is divided into 5 equal 10 keVee bins.

As described in Section 4 it is difficult to be certain about neutron pulses. In order to improve the reliability of the neutron pulses the TOF neutrons in bins 4 through 8 were cleaned using charge-integration PSD. After using PSD we have more confidence that the measured, TOF-attributed neutron pulses are in fact neutron pulses. As shown in Fig. 7 the overlap in neutron and gamma-ray pulses occurs below the discrimination line. Therefore by only using pulses above the discrimination line in bins

4 through 8 we are sure these pulses are all neutrons. In Fig. 11 only up to 0.625 of the energy window is plotted since bins 1 through 3 are not present in the plot.

In Fig. 11, the lowest 4 points for methods 4 and 5 are not shown. This is because these two methods over identify pulses as neutrons, as seen in Fig. 10, and classified each of the neutrons as neutrons so had a zero fraction of false negatives. Also from Fig. 11 we can see that method 3 outperforms method 2. From both Figs. 10 and 11 method 3 was chosen as the comparison method of choice because it was able to identify both neutrons and gamma rays with the lowest combined fraction of false negatives.

7. Hybrid PSD method

The proposed hybrid PSD method uses the charge-integration method for pulse heights above 70 keVee and the reference-pulses PSD method for pulse heights below 70 keVee. For each of the eight pulse height bins 14,000 TOF-attributed neutron pulses and 14,000 ^{137}Cs gamma-ray pulses were used to test the hybrid PSD method. Fig. 12 shows the results of the hybrid PSD method compared to the charge-integration PSD for the neutron pulses.

The largest improvement is observed in the smallest pulse height bin corresponding to 200 keV neutron energy deposited, where the hybrid method gave a 32% improvement over the charge-integration method. The results from the ^{137}Cs gamma-ray pulses are shown in Fig. 13.

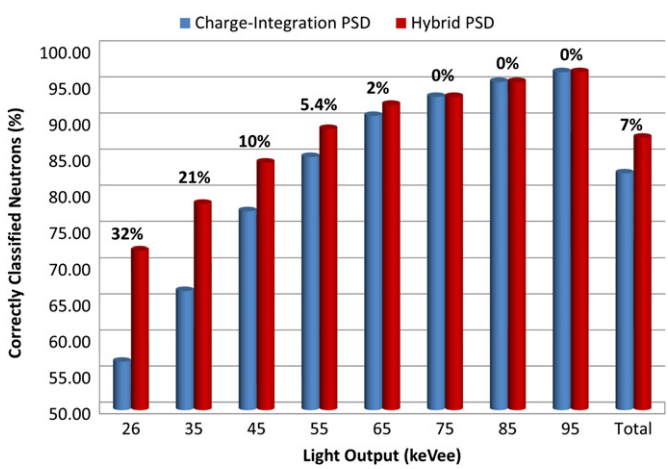

Fig. 12. Comparison of the PSD methods for TOF-attributed neutrons.

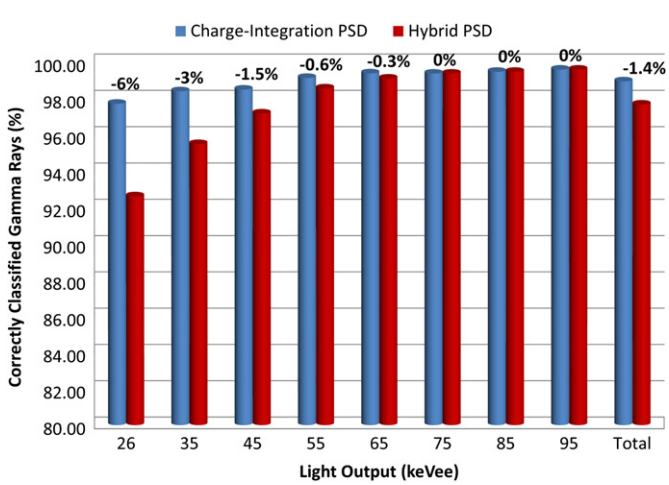

Fig. 13. Comparison of PSD methods for known gamma-ray pulses.

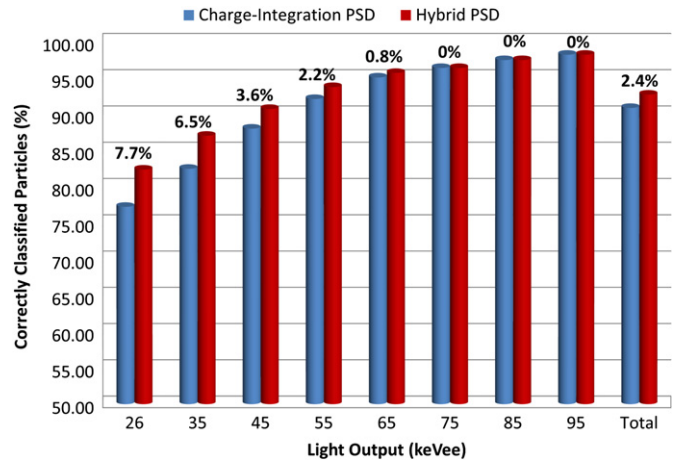

Fig. 14. Mixed particle classification for an equal number of neutrons and gamma rays using the hybrid PSD and charge-integration PSD.

For gamma rays, the charge-integration PSD outperforms the hybrid PSD at low pulse heights. This performance is due to the discrimination line used for the charge-integration PSD. As can be seen in Fig. 7, the line was chosen so that the gamma-ray pulses will always be beneath the line, therefore always identifying them as gamma rays. It should be pointed out that the hybrid method correctly identified approximately 92% of the gamma rays. An equal number of known neutron and gamma-ray pulses in each light output bin were used to compare the PSD methods and the result is shown in Fig. 14. This is a more realistic comparison in which the hybrid PSD outperforms the charge-integration PSD by several percent in all light output bins lower than 70 keVee. This is very promising for measurements taken in mixed neutron and gamma-ray fields.

8. Conclusions

We presented a new, hybrid PSD approach that makes use of two digital PSD methods: the standard charge-integration PSD method and a new, reference-pulses PSD method. The two methods are applied to individual digitized pulses depending on the measured pulse height. Our results demonstrate that the method gave considerable improvement over the charge-integration method for light output bins below 70 keVee (corresponding to a neutron energy deposition of approximately 500 keV). At a neutron energy of 200 keV an overall improvement of approximately 8% is observed over the charge-integration technique in mixed particle tests (with an equal number of neutron and gamma-ray pulses). An improvement of 32% is observed for 200 keV neutrons. It must be pointed out that it is difficult to test the approach on neutron pulses since all neutron sources have a significant gamma-ray background. This makes acquiring pure neutron pulses very challenging. The performance of the method is difficult to quantify because the percentage of accidental gamma rays in each neutron bin is not accurately known. Looking at the gamma-ray results gives a clearer picture of how accurately this method works. Since the gamma rays tested were from a ^{137}Cs source the only neutron or non-gamma rays possible are from cosmic and environmental background and make up a sub percentage of pulses. At the lowest pulse height bin of 20–30 keVee, which corresponds to 20–30 keV deposited gamma-ray energy the hybrid PSD technique correctly classified 92% of the pulses. Over all eight gamma-ray bins the hybrid PSD technique averaged 97.8% for correctly identifying the gamma rays.

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