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Title: Application of digital zero-crossing technique for neutron-gamma discrimination in liquid organic scintillation detectors

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Application of digital zero-crossing technique for neutron-gamma discrimination in liquid organic scintillation detectors

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Abstract

An algorithm for digital implementation of the zero-crossing method for n/γ discrimination in liquid organic scintillators is described. The method exhibits good performance at low energies and requires little computational effort, which makes it suitable for compact real-time neutron detectors.

Keywords: Digital pulse shape discrimination, Liquid scintillator, Neutron detection

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1. Introduction

One of the most effective methods of fast neutron detection is the use of organic scintillator detectors coupled to photomultipliers together with a neutron-gamma (n/γ) pulse-shape discrimination technique. The n/γ discrimination method described in this paper utilizes a difference in the intensity of the slow component of the light pulse in the organic scintillator, generated by the recoil proton and electrons [1]. The two most common methods of exploiting this property of liquid scintillator detectors for n/γ discrimination using analogue electronics are the charge-comparison [2,3] and zero-crossing techniques [4,5]. The charge comparison method is based on independent measurements of the integrated charge over two different time regions of the pulse. In the zero-crossing method, information on the particle type is obtained from the zero-crossing time of the suitably shaped signal.

The development of fast analogue-to-digital converters and the use of digital processors allows the implementation of conventional n/γ discrimination methods with field programmable gate array (FPGA) technology and also the application of the new digital signal processing methods for n/γ discrimination. There are several methods of digital n/γ discrimination such as the fitting of a predefined response function to each pulse [6], pulse gradient analysis [7] and frequency-domain analysis [8], which have been solely applied in the digital domain. However, due to the susceptibility of these methods to electronic noise or intensive computation time, the double integration method, which is a digital version of the conventional analogue charge-comparison method, is mostly used [9-12].

In this paper an algorithm for digital implementation of the conventional zero-crossing method is described. The algorithm shows better performance than the charge-comparison method in the low-energy range and requires a short pulse-shape computation time, which makes it suitable for portable and compact real-time neutron detectors, for applications such as neutron dosimetry and the detection of illicit nuclear material.

2. Experimental details

A cylindrical NE213 liquid scintillator (5.08 cm diameter and 5.08 cm long) coupled to a photomultiplier tube (PMT) of type R329 Hamamatsu was used to characterize the pulse-shape discrimination algorithm. A diagram of the experimental set-up is shown in Fig. 1. The detector container is made of aluminum and the PMT is mounted on the back circular surface of the detector. The PMT was operated with a negative voltage of 1500 V and the signals from the anode of the PMT were directly digitized using a digital oscilloscope with a sampling rate of 1GSample/s and 8-bit resolution.

Tests were performed using a readily available americium-beryllium (Am-Be) neutron source and more than forty thousand pulses were stored on the hard drive of the oscilloscope. A range of γ-ray sources was also used initially to characterize the energy performance of the scintillator. The digitized pulses were transferred to a personal computer for analysis. The analysis is performed using a program written in MATLAB language.

3. n/γ discrimination algorithm

Fig. 2a shows typical pulse shapes of the NE213 liquid scintillator detector for neutrons and γ-rays. The neutron pulse exhibits a larger decay time to the base line which is due to the greater proportion of the slow scintillation component. The digital zero-crossing method exploits this property by applying a digital differentiator-integrator-integrator (C_1R_1-$(R_2C_2)^2$) pulse shaping network to the PMT current signals. As shown in Fig. 2b, the shaping process converts the PMT signal to a bipolar pulse in which the difference in the decay time of different PMT signals is reflected in the zero-crossing time of the shaped signals. In order to exploit the difference in the zero-crossing time as a parameter for n/γ separation, a digital constant fraction discriminator (CFD) is used to determine the start time of the signal and then the delay between the start time and the time at which the shaped signal crosses the zero line is determined. The digital CFD acts by finding the signal's maximum value and setting a threshold based on a predefined fraction of this maximum. The pulse is then analysed to determine when it initially crosses this threshold. The time pickoffs of the signal start time and zero-crossing time are linearly interpolated if they fall between the signal samples.

4. Performance studies

In order to evaluate the performance of the method, particularly over different energy ranges, the energy scale of the system was calibrated using the Compton edge of standard ^{60}Co, ^{137}Cs and ^{22}Na γ-ray sources. The energy calibration was done using the channel number at 75% of the Compton edge maximum [13]. The results of the calibration together with the associated pulse height spectra are shown in Fig. 3.

The result of applying the n/γ discrimination method strongly depends on the time constants of the differentiator and integrator involved in the pulse shaping process. Therefore, it is necessary to optimize the two time constants according to the best separation quality. The quality of n/γ separation may be checked by determination of the figure-of-merit (FOM), defined as:

$$FOM = \frac{S}{FWHM_n + FWHM_\gamma} \qquad (1)$$

Where S is the separation between the peaks of the neutron and γ-ray events and $FWHM_\gamma$ and $FWHM_n$ are, respectively, the full-width-at-half-maximum of the spread of the neutron and γ-rays peaks [14]. To determine the optimum shaping time constants, the CFD fraction, involved in the determination of signal start time, was set at 0.3 and a series of FOM calculations at different time constant settings were completed for the same events. In the calculations, FWHMs were determined by fitting Gaussian functions to the neutron and γ-ray events. It was found that the best performance is achieved with a differentiation time constant (C_1R_1) of 10 ns and an integration time constant (R_2C_2) of 47 ns. It is obvious that these optimum time intervals depend on the detector type and the PMT and therefore should be determined for the specific apparatus concerned. Using the optimum time settings, the FOM of the separation is 0.48 at an energy threshold of 50 keVee (equivalent electron energy) which improves to 1.51 at an energy threshold of 350 keVee. The performance of the n/γ discrimination for different threshold energies is shown in Fig. 4. It is seen that the γ-rays and neutrons are almost completely separated for threshold settings above 350 keVee, while a relatively good discrimination is achieved even for a setting as low as 50 keVee. The good performance of the method at low energy thresholds is due to the fact that the pulse shaping process effectively removes the electronic noise, which is otherwise the cause of poor discrimination at low energies.

The performance of the zero-crossing method was compared with a digital implementation of the conventional charge-comparison method. The charge-comparison method was carried out by integrating each signal over two time intervals of Δt_F and Δt_S (see Fig. 2a) providing the fast and slow components of the signal. The value of the charge ratio was then calculated in order to characterize the neutron and γ-ray events. The optimum time intervals of charge integration were determined by calculation of the FOM value multiple times over different time intervals. It was found that the best results are obtained at time intervals of ~20 ns and ~170 ns, respectively, for Δt_F and Δt_S. A comparison of the scatter plots of the n/γ separation using the charge-comparison and zero-crossing methods for an energy threshold of 50 keVee is shown in Fig. 5. Fig. 6 shows a comparison of the FOM values as a function of threshold for both methods. The better performance of the zero-crossing method is apparent over the whole of the examined energy range.

Since the zero-crossing method is a timing method and the performance of digital timing methods strongly depends on the signal sampling rate, we have investigated the effect of the sampling rate on the performance of the method. In our test, the original data were acquired at 1GSamples/s and 8-bit resolution and then recalculated as if they had been acquired with reduced sampling rate. Such data were used for simulation of the digitizer operation at 500, 250 and 125 MSamples/s. The n/γ separation as a function of signal sampling rate is shown in Fig. 7. It is seen that at lower sampling rates the separation quality is reduced. However, a better n/γ discrimination is expected for digitizers with higher digitization accuracy as it is known that the accuracy of digital timing is primarily determined by the digitization accuracy [15].

5. Conclusion

We have presented a digital version of the zero-crossing n/γ discrimination method for organic liquid scintillator detectors. The method offers a high degree of immunity to electronic noise. This relies on the fact that the pulse shaping process effectively removes the electronic noise, which limits the n/γ discrimination at low energies. The method requires little computation effort, which makes it suitable for real-time neutron detectors for various applications.

Acknowledgment

We acknowledge support from the UK STFC and AWE plc and we thank the referee for useful suggestions.

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Figures captions

Figure 1. Diagram of the experimental setup.

Figure 2. (A) Typical sample of PMT signals for neutrons and γ-rays. The signals approximately correspond to 500 keVee. The neutron pulse decays more slowly than the

γ-ray pulse. (B) PMT signals after the pulse shaping process. The neutron and γ-ray pulses cross the zero line at different times.

Figure 3. Pulse height distribution from ^{60}Co, ^{137}Cs and ^{22}Na. The inset shows the calibration data using the Compton edges from the γ-ray spectra.

Figure 4. The n/γ discrimination for different energy thresholds.

Figure 5. Top: the scatter plot of charge comparison. Bottom: the scatter plot of zero-crossing. A better separation is achieved with the zero-crossing method.

Figure 6. A comparison of FOM values as a function of energy threshold for charge-comparison and zero-crossing methods. The better performance of the zero-crossing method is apparent over the whole of the examined energy range.

Figure 7. n/γ separation as a function of digitizer sampling rate. The energy threshold is 100 keVee. The separation quality decreases at lower sampling rates. The FOM values for 1 GS/s, 500, 250 and 125 MS/s are, respectively, 1.143, 1.03, 0.94 and 0.8.

Figure(1)
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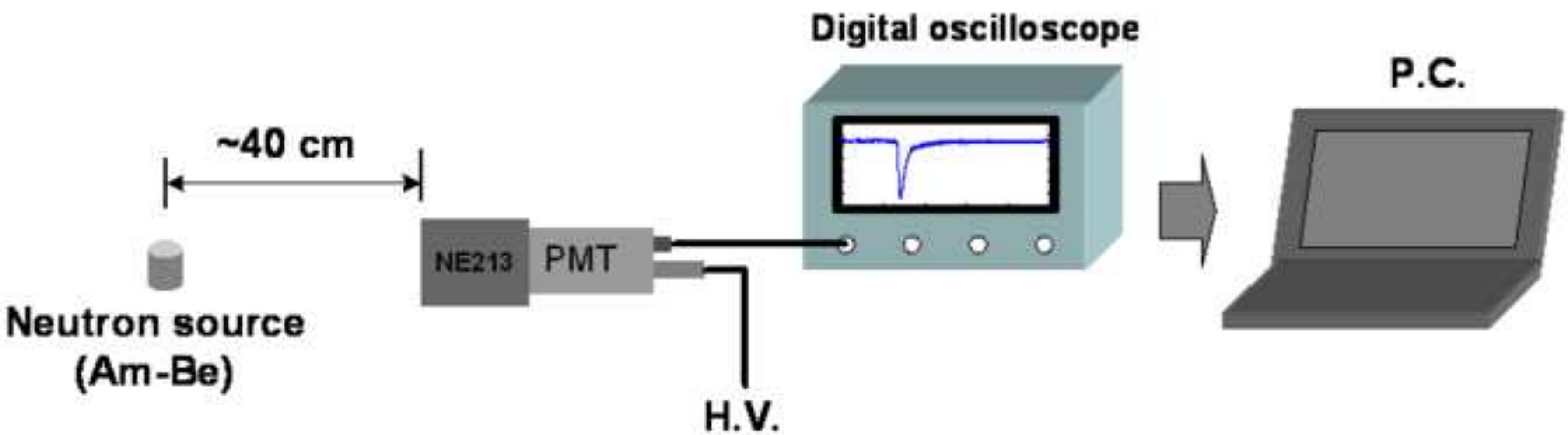

Figure(2)
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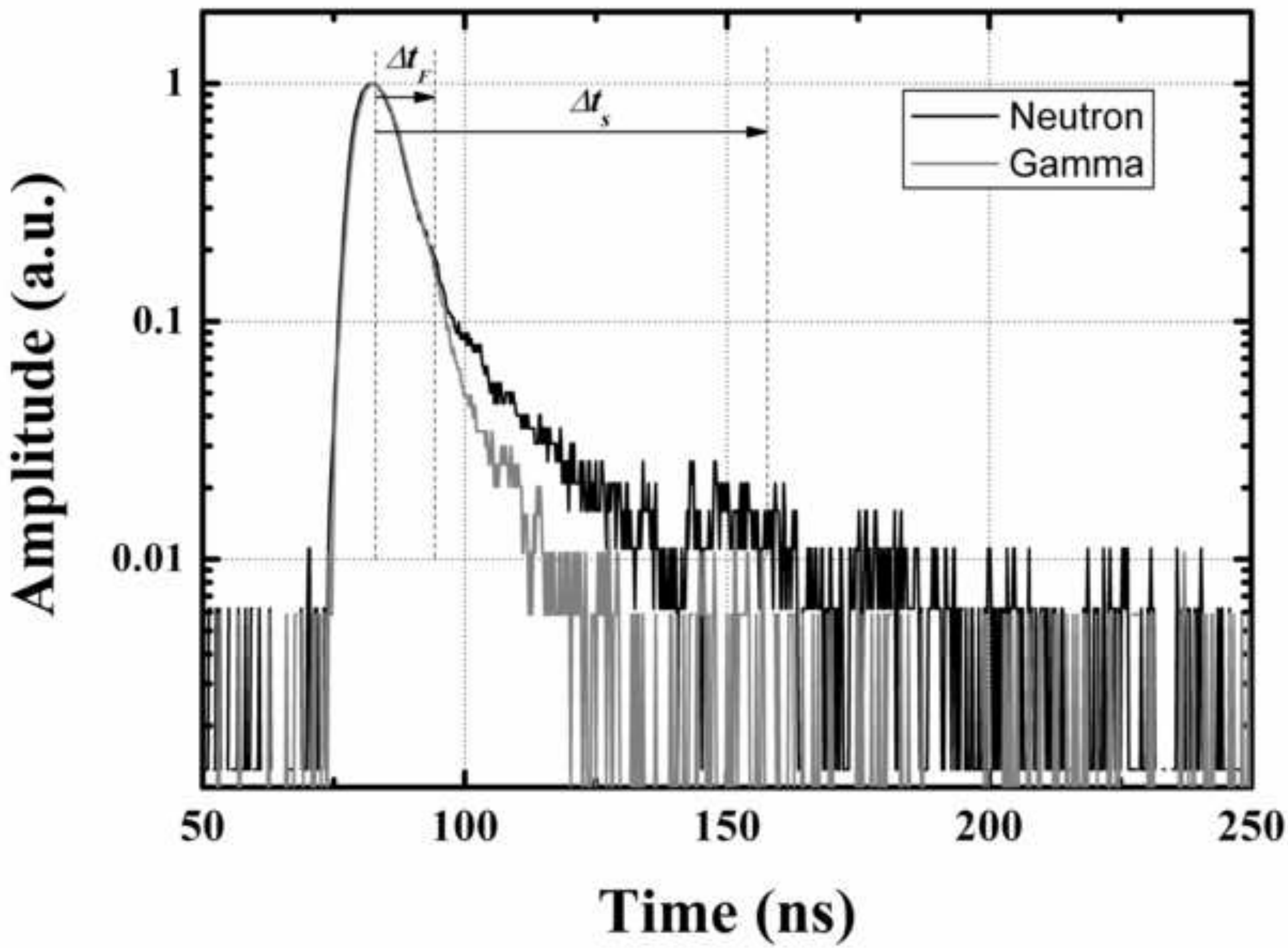
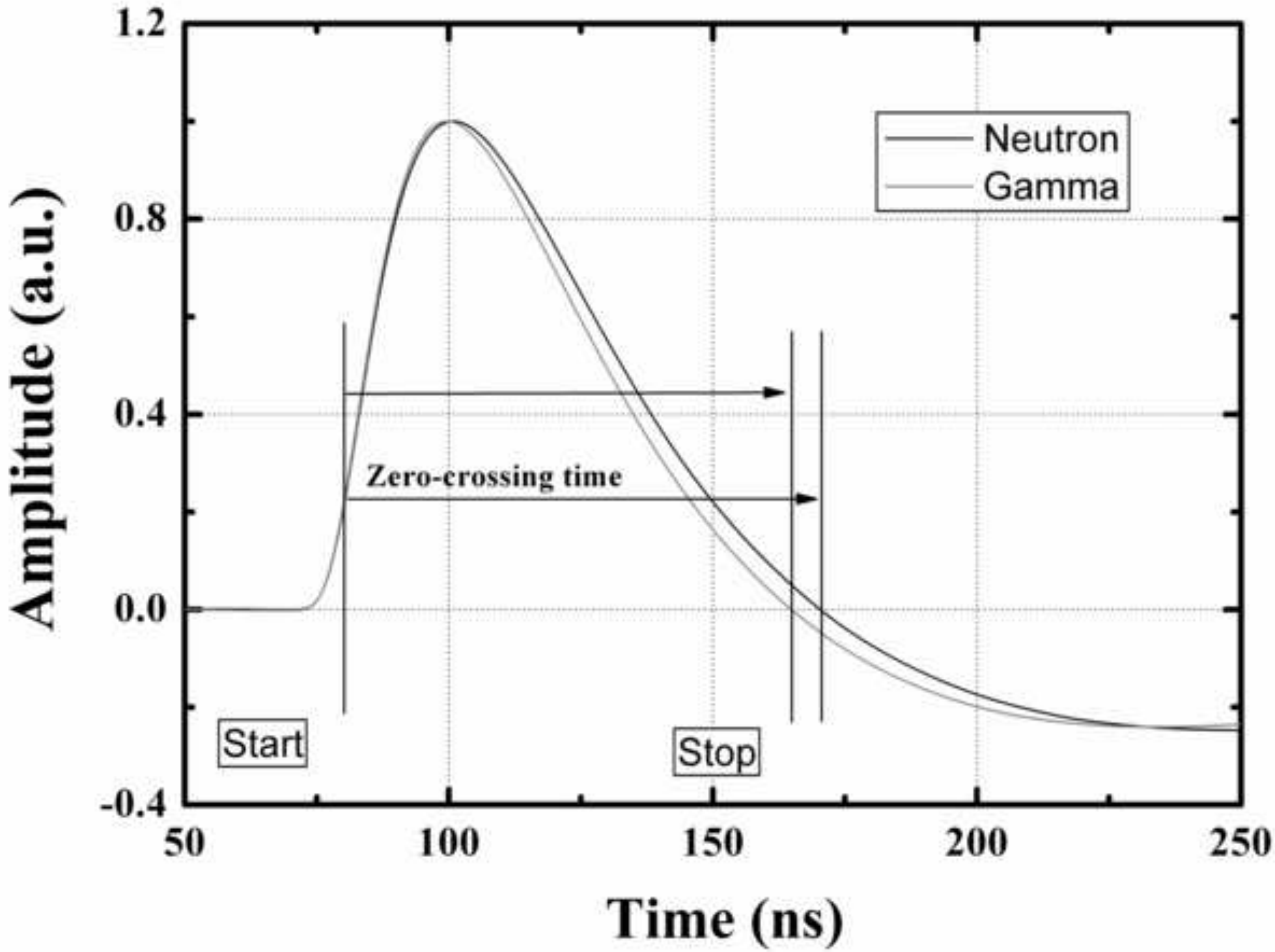


Figure(2-b)


1.2
0.8
0.4
0.0
-0.4
50
100
150
200
250
Amplitude (a.u.)
Time (ns)
Neutron
Gamma
Zero-crossing time
Start
Stop

Figure(3)
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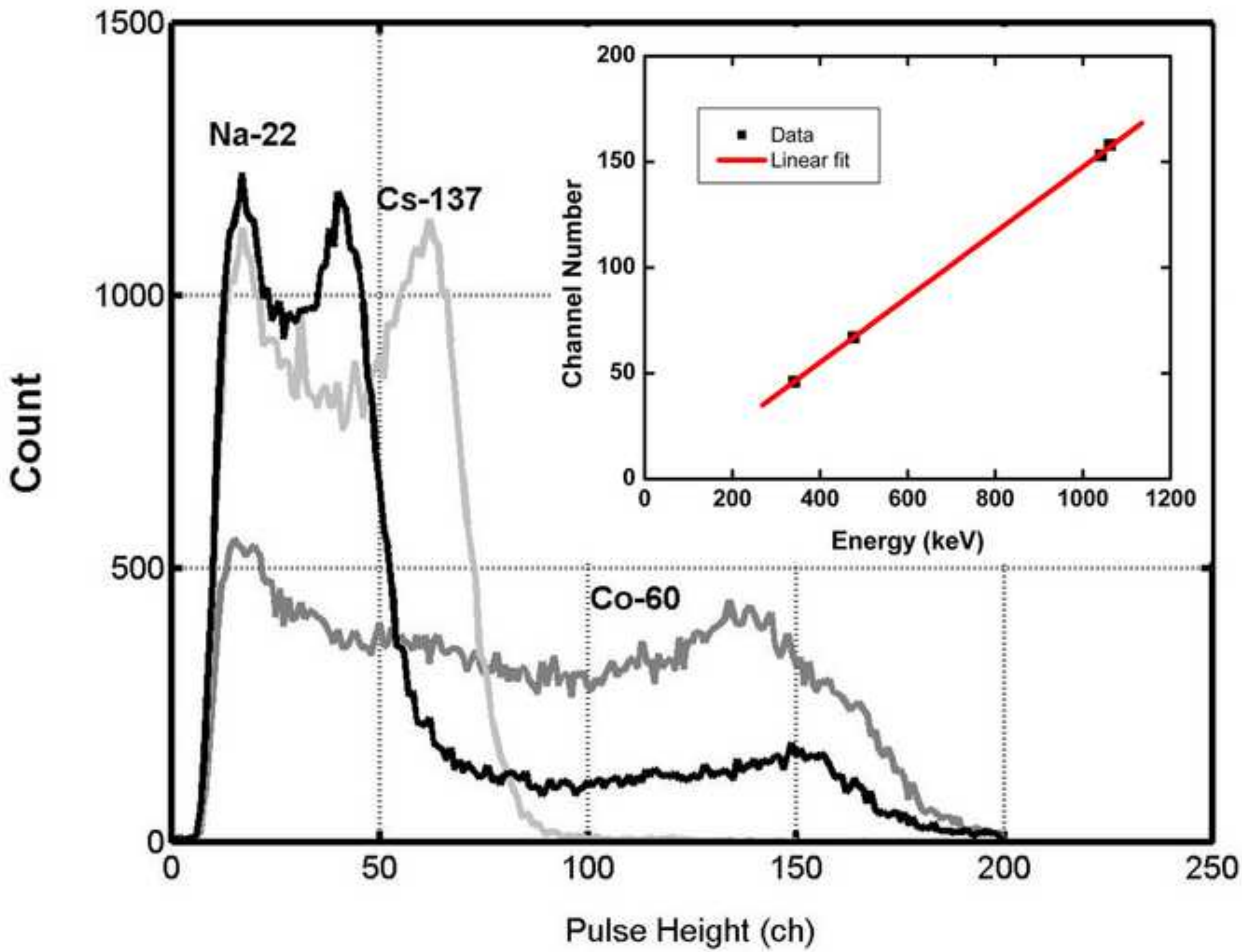

Figure(4)
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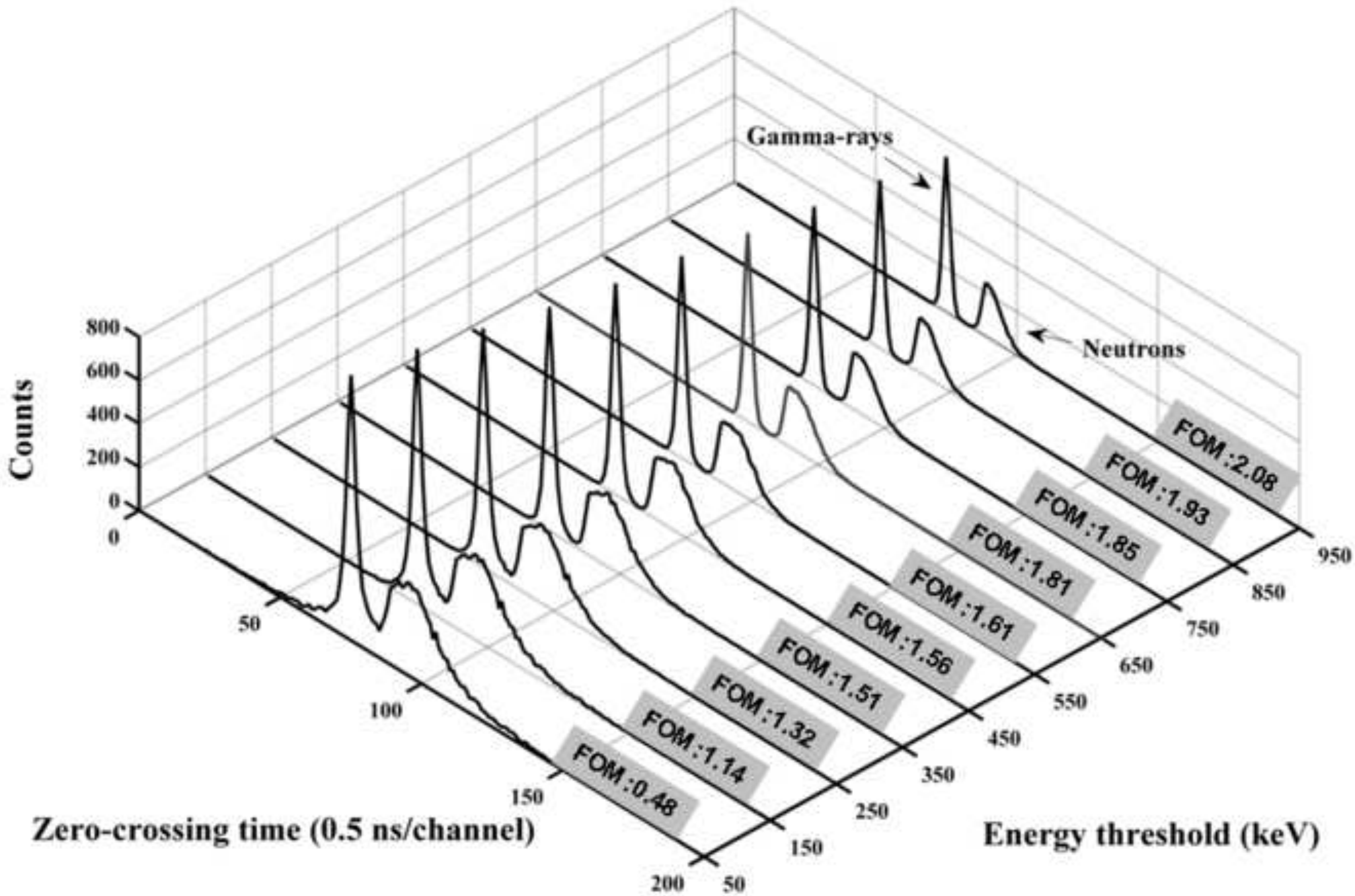

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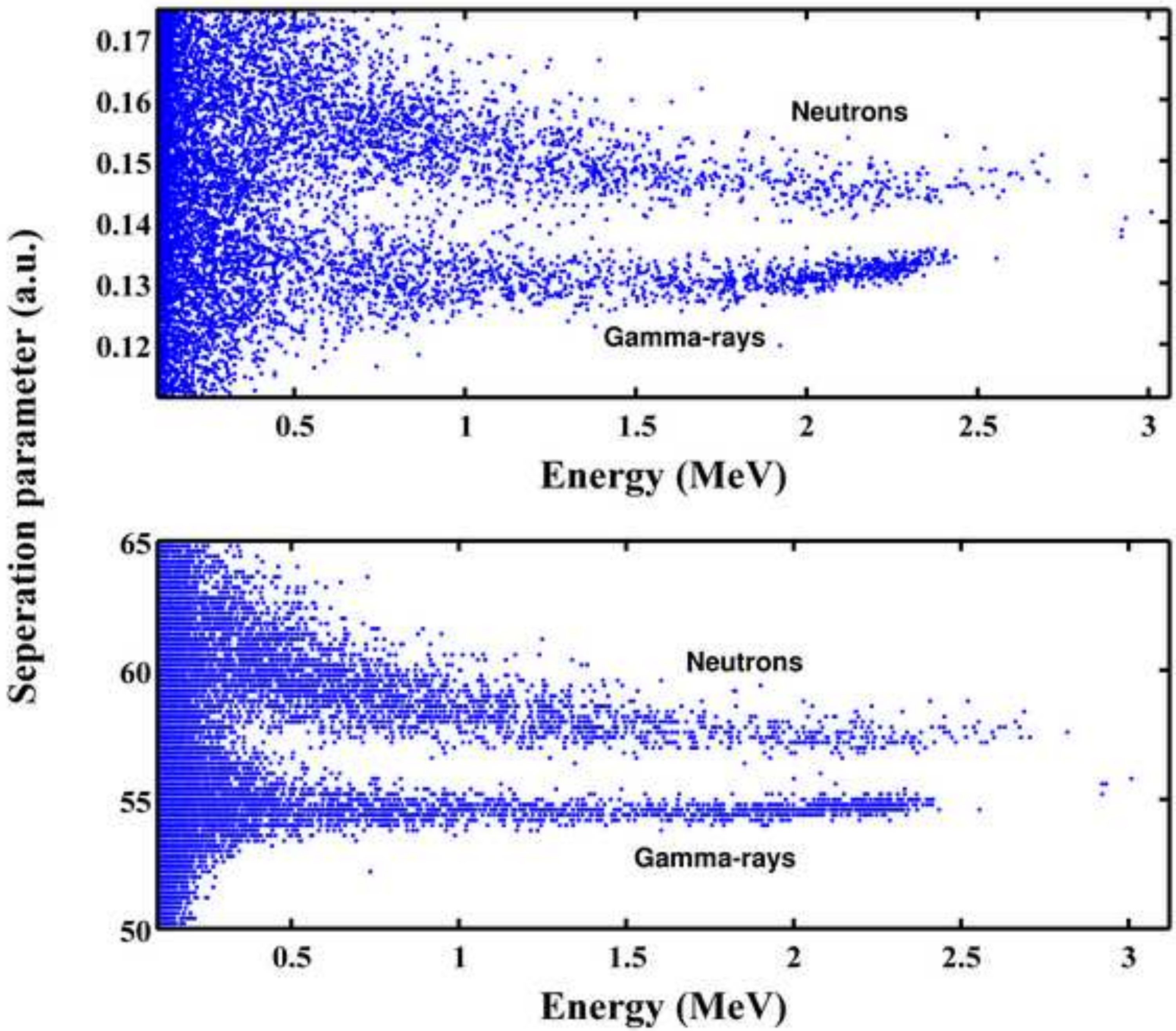
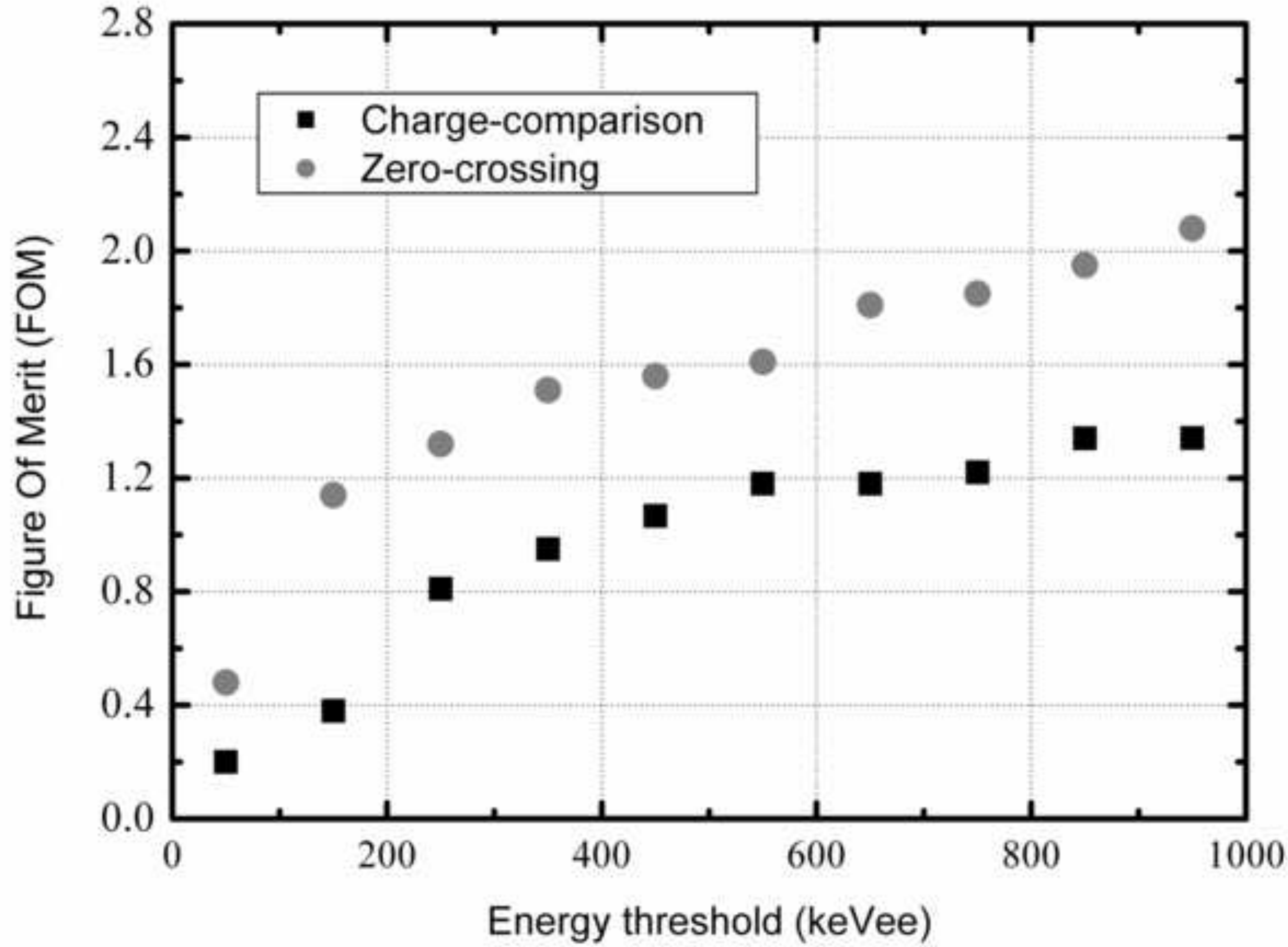


Figure(6)


Charge-comparison
Zero-crossing
Figure Of Merit (FOM)
Energy threshold (keVee)
0.0
0.4
0.8
1.2
1.6
2.0
2.4
2.8
0
200
400
600
800
1000

Figure(7)
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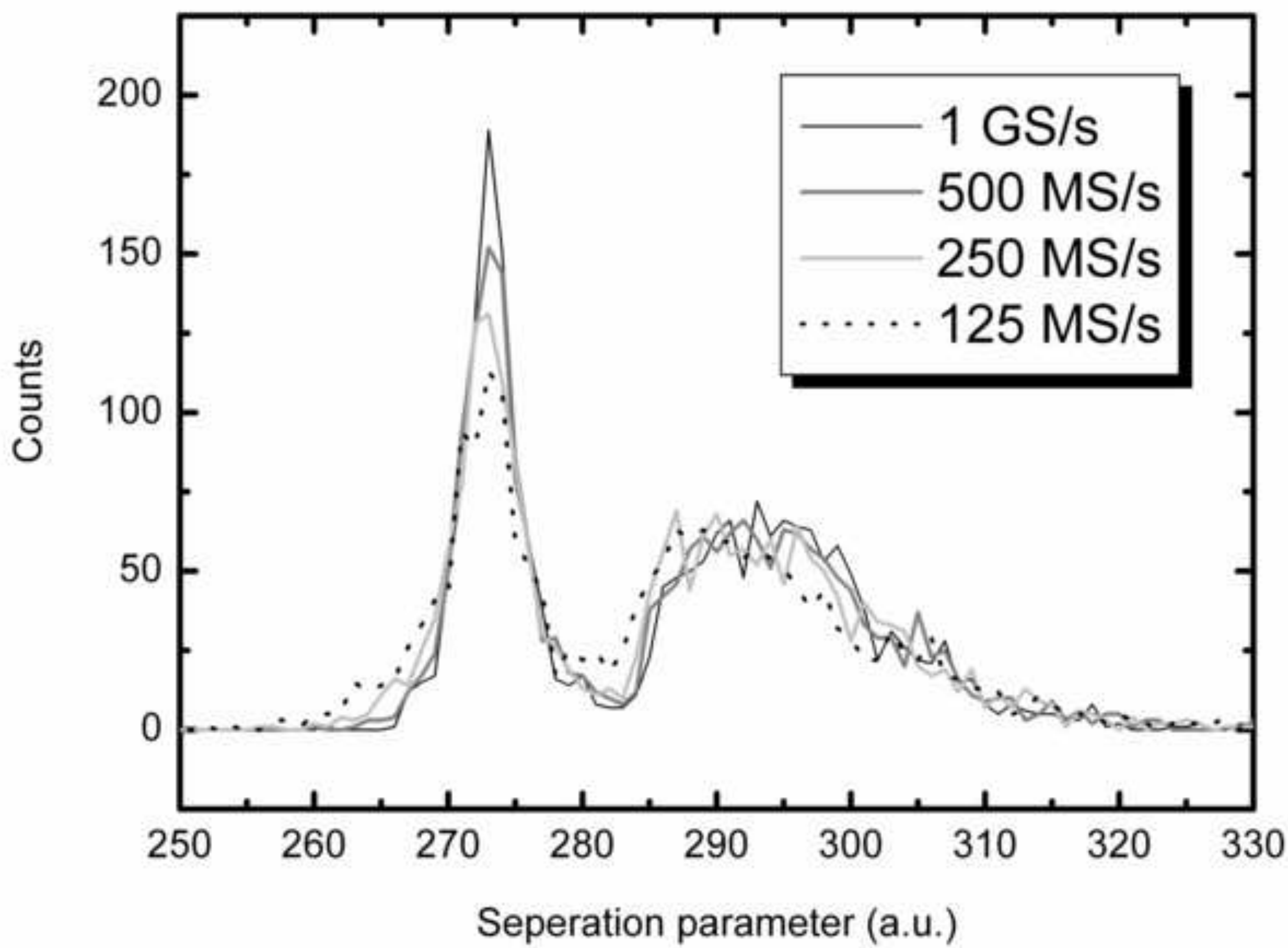

***Response to Reviewers &/or Editor**

List of changes

Dear Prof. Wehe and reviewer,
Thank you very much for your careful reading and useful comments in the preparation of this article. I have addressed each of the specific points raised by the reviewer point by point below and have made the requested typographical changes to the text of the paper.

Referee's Comments

1. Page 2, line 29,
Comment: SI unites are preferable, i.e. 5.08 cm should be used instead of 2".
RESPONSE: Done. Detector size is now expressed in SI units (Page 2, line 30 in the revised manuscript).

2. Page 2 line 30
Comment: photograph or a diagram of the experimental setup would be useful.
RESPONSE: Done. A diagram of the experimental setup is now added to the manuscript (Page 3, line 3 and Fig.1 in the revised manuscript).

3. Page 3, line 4,
Comment: This alpha-n source emits a large number of gamma rays compared to neutrons. Therefore, the author should briefly explain why this type of the neutron source was used. Perhaps this was the most convenient choice (the only source available)?
RESPONSE: Done. "a readily available" has been added to the text to clarify that the Am-Be source was used due to its availability. (Page 3, line 6 in the revised manuscript).

4. Page 4, line 20
Comment: "keVee" should be used instead of "keV" throughout the paper, including the threshold axis in Fig. 3, unless neutron energy deposited is meant. In that case, "neutron energy deposited" should be explicitly stated.
RESPONSE: Done. In all the manuscript "keV" has been changed to "keVee".

5. Page 4, line 20,
Comment: A figure showing FOM values as a function of threshold would be beneficial. Alternatively, Fig. 3 could be modified by adding a FOM value to each plot.
RESPONSE: Done. The FOM values have been calculated for different energy thresholds and are now inserted in the Figure (Fig.4 in the revised manuscript).

6. Page 4, line 23,
Comment: FOM values of more than one are considered "good"; therefore, this expression should be changed to "relatively good".
RESPONSE: "good discrimination" has been changed to "relatively good discrimination" (Page 4, line 27 in the revised manuscript).

7. Page 5, line 8,

Comment: It would be beneficial to compare FOM values as a function of threshold for both PSD methods in a single figure. Such figure would clearly illustrate the difference in the PSD performances. In addition, it would be interesting to assess what such FOM means from the practical point of view, i.e. what percentage of neutrons and/or gammas is expected to be falsely classified (expected gamma rejection number).
RESPONSE: Fig.6 which shows a comparison of the FOM value as a function of threshold has been added (Fig.6, Page 5, line 12, revised manuscript). The better performance of the zero-crossing is apparent over the whole of the examined energy range.

8. Page 6, line 21.

Comment: The noise in the pulses looks fairly low. The figure caption should mention what pulse heights (in light-output units, i.e. keVee) are shown.
RESPONSE: Done. The pulse amplitudes are fairly high. Information on the signal's amplitude has been added to the caption of the Figure (Fig. 2 in the revised manuscript).

9. Page 7, line 2,
   Comment: Figure should be modified by adding a separate line-type label for each curve (line sample first, then digitizer sampling rate), for example in the top right corner. In this case, it is fairly intuitive what is what, but the figure might be confusing for a first-time PSD reader.
   RESPONSE: Done. Figure has been modified accordingly.

Typographical Corrections:

1. Page 2, line 2, "the n/γ" was changed to "a neutron-gamma (n/γ)" (Page 2, line 2 in the revised manuscript).

2. Page 2, line 4, "described in this paper" was added (Page 2, line 3 in the revised manuscript).

3. Page 2, line 12, "analogue to digital" was changed to "analogue-to-digital" (Page 2, line 13 in the revised manuscript).

4. Page 2 line 15, "exist" was replaced with "are" (Page 2, line 16 in the revised manuscript).

5. Page 2, line 25, "real time" was changed to "real-time" (Page 2, line 26 in the revised manuscript).

6. Page 3, line 1, "high" was omitted (Page 3, line 3 in the revised manuscript).

7. Page 3, line 3, "storage" was omitted (Page 3, line 4 in the revised manuscript).

8. Page 3, line 5“disk” was omitted (Page 3 line 7 in the revised manuscript).

9. Page 3, line 11, “Fig. 2A” was changed to “Fig. 2 a” (Page 3 line 14 in the revised manuscript).

10. Page 3, line 16, “Fig. 2B” was changed to “Fig. 2 b” (Page 3 line 19 in the revised manuscript).

11. Page 4, line 28, “charge comparison” was changed to “charge-comparison” (Page 5, line 4, revised manuscript).