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PULSE-SHAPE DISCRIMINATION FOR IDENTIFICATION OF NEUTRON SOURCES USING THE BC-501A LIQUID SCINTILLATOR

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ABSTRACT

Fast and accurate identification of neutron sources is very important in nuclear nonproliferation and international safeguards applications. Commonly, the identification of neutron spectra relies on unfolding procedures, which requires the solution of an ill-posed problem. In this paper, we present a new application of an existing technique, which can be used for neutron source identification without employing energy-spectrum unfolding techniques. This technique is based on the acquisition of measured neutron pulse-height spectra by using a liquid scintillation detector BC-501A and a fast waveform digitizer TDS-5104. The technique employs an optimized digital pulse-shape discrimination method based on the standard charge integration method to discriminate neutrons from gamma rays. The accuracy of the neutron-source identification method was tested on three neutron sources: californium-252 (Cf-252), americium-beryllium (Am-Be), and americium-lithium (Am-Li). Several source-shielding configurations were investigated to assess the influence of potential shielding of the source on the accuracy of the method. This aspect was addressed by using lead and polyethylene shielding blocks. The measured pulse-height distributions were compared with the distributions simulated with the MCNP-PoliMi code, and excellent agreement was obtained for the Cf-252 and the Am-Be sources. The agreement for the Am-Li source was less favorable due to the uncertainty of measured data. The final results show that for all tested source-shielding configurations, the identification of the Cf-252, Am-Be, and Am-Li sources by direct analysis of the measured pulse-height distributions is very straightforward, and no subsequent neutron energy-spectrum unfolding is required.

Key Words: neutron source identification, liquid scintillator, waveform digitizer, pulse-shape discrimination

1. INTRODUCTION

Accurate knowledge of the spectrum of neutrons emitted by nuclear materials is of great interest in many research applications, including nuclear nonproliferation, international safeguards, nuclear material control and accountability, national security, and counterterrorism. Specifically, for safeguards applications it is very important to develop new methods that facilitate fast and robust identification of neutron sources such as californium-252 (Cf-252), americium-beryllium (Am-Be), and americium-lithium (Am-Li) neutron sources.

The popularity of liquid scintillation detectors for neutron/gamma-ray detection originates in their excellent pulse-shape discrimination (PSD) properties and fast timing performance [1–5]. A neutron and gamma-ray PSD using liquid scintillation detectors is a widely adopted technique in the nuclear fields. In contrast to thermal neutron detectors, liquid scintillators are able to detect high-energy neutrons without the use of a moderating material. The difference in the intensity of slow neutron and gamma-ray light components serves as a basis for PSD methods used to identify and characterize neutron pulses. Several analog methods for PSD have been developed and studied in the past, including charge-comparison and rise-time methods [6,7]. Numerous improvements have been made to the PSD properties of liquid scintillators to make them more suitable for applications in high count-rate fields. The first important improvement has been achieved by optimizing the size and shape of detectors [8]. The second major improvement involved the rapid development of waveform digitizers, which has increased the measurement count rate and maximized the amount of information that can be obtained from a detector. Initial investigations to achieve the latter were begun in the early 1980s [9].

Identifying neutron sources with organic liquid scintillators using digital PSD techniques is a very promising method that is based on the observable differences between the neutron pulse-height spectra of the various sources. In this paper we present a new application of an existing technique that acquires neutron pulse-height spectra using a liquid scintillation detector and a fast digitizer. This technique is used for fast and accurate identification of shielded neutron sources based on the direct analysis of the pulse-height spectra. Unlike traditional neutron-source spectra unfolding techniques, this technique relies on the results of the PSD analysis of a large number of neutron and gamma-ray pulses from a neutron source with or without shielding. This technique is fast, robust, and results in the highly accurate identification of different neutron sources.

In order to verify the quality of the neutron pulse-height distributions acquired from measured data, we compared them with distributions simulated using the MCNP-PoliMi code [10], which is an advanced modification of the standard MCNP code [11]. Among other calculations, this code allows for accurate simulations of pulse-height distributions for various detectors, taking into account the physical processes governing the pulse creation. Finally, to assess the influence of the potential shielding surrounding the source, and to assess the sensitivity of the PSD technique under different conditions, several source-shielding configurations were tested. In a real-world scenario, the probability of the presence of source shielding is relatively high. Therefore, we addressed this aspect by using shielding blocks made of lead (Pb) and polyethylene (PE).

2. DATA MEASUREMENT AND PSD METHOD

A 5GS/s digital oscilloscope Tektronix TDS-5104 was used to store tens of thousands of pulses from the anode of a liquid scintillator BC-501A. The pulses were collected directly from an anode of a photomultiplier (PMT). Each pulse was recorded with a time resolution of 0.2 ns. The PMT had the same diameter as the scintillator. The digitizer was connected to the anode of the PMT via 50 Ω impedance. All data was postprocessed by using scripts in Matlab® language. The BC-501A that was used is 7.7 cm thick and has a diameter of 15.2 cm. In these experiments, the total time range was limited to 200 ns per pulse. A digital PSD technique based on ratios of pulse integrals over different time periods was optimized and applied to discriminate neutrons from gamma rays. This technique is a digital version of the well-known analog charge integration method. Three neutron sources were used for investigation: Cf-252, Am-Be, and Am-

Li. These sources have distinct neutron energy spectra, both in shape and average neutron energy. The neutron sources Cf-252 and Am-Li were placed at a distance of 50 cm from the detector. The Am-Be source was placed 30 cm from the detector due to its size (it is permanently surrounded by polyethylene and stainless steel). The investigated shielding blocks were attached to the front face of the detector.

2.1. The PSD Method

A ratio of two areas obtained by integration of the pulse in various time intervals is used to discriminate neutrons from gamma rays. The area A_1 is the total area of the pulse, while the area A_2 represents the tail of the pulse. The ratio R is defined as

$$R = \frac{A_2}{A_1} \quad . \tag{1}$$

The integral ratio R for the correctly applied PSD method is higher for most of the neutron pulses when compared to the gamma-ray pulses, as shown in Fig. 1.

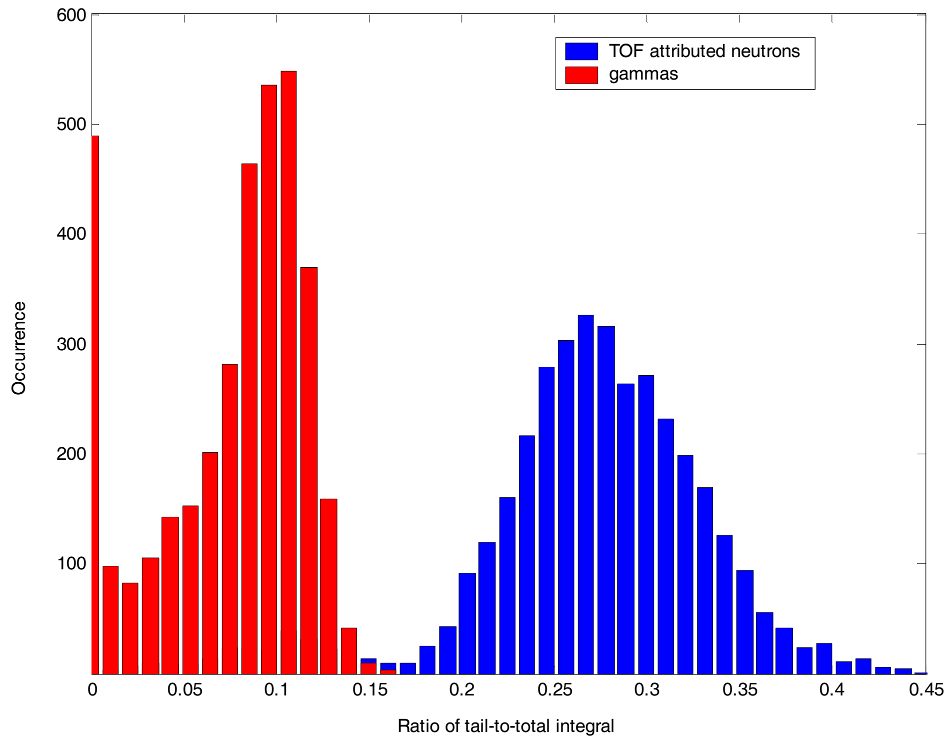

Figure 1. Histograms of known neutron and gamma-ray pulses obtained by using the optimized range of the tail integral.

This unique feature is used to separate the neutrons from the gamma rays. The relatively high value occurring in the gamma-ray histogram at position zero is attributable to the accumulation of low-ratio values (negative R values are not possible). The cross point of the neutron and the gamma-ray curve has been chosen as a discrimination point used to classify the particles detected. Above the classification point, all pulses are classified as neutrons, whereas below this point, the pulses are classified as gamma rays. In Fig. 1, the overlap area is approximately 3% of the total area of the neutron and gamma-ray distributions. Most of these pulses are neutrons, which means that only a very small number of gamma rays are misclassified using the known pulses.

2.2. Optimization of the PSD Method

To optimize the PSD method, neutrons and gamma rays from different radioactive sources were measured separately. The neutrons emitted by a Cf-252 source were detected using the time-of-flight (TOF) method, which allows direct identification of the neutron pulses in a gamma-ray background. The Cf-252 source was placed in the middle of an ionization chamber at a distance of 1 m from the detector. The ionization chamber served as a “start” detector to determine time “zero”. The gamma-ray pulses were measured using a cesium-137 (Cs-137) source placed on the face of the detector. It should be noted that due to accidental coincidences, a small number of gamma-ray pulses were attributed to neutron pulses.

The number of misclassified neutrons and gamma rays were minimized by optimizing the integration range of the tail integral and the location of the classification point. The optimizations were performed such that the overlap area of neutron and gamma-ray distributions has been minimized [12]. The starting point of the tail integral was set to 11 ns from the peak of the pulse, and the end point was set to 170 ns from the peak of the pulse. The possible optimization of the range of the total integral was eliminated by setting the total pulse range in the measurements to a fixed value of 200 ns, while the optimization of the pulse-height threshold was abandoned due to the consequent loss of information in the neutron low-energy range.

3. RESULTS

3.1. Measurements with Cf-252, Am-Be, and Am-Li Neutron Sources

For each source-shielding configuration, about 27,000 neutron and gamma-ray pulses were acquired. In general, Pb shielding eliminates a high number of gamma rays, thus more neutrons per acquisition are detected, and the statistical accuracy of measured pulse height is improved. PE shielding, on the other hand, results in a lower number of neutrons per acquisition, which negatively influences the statistics of the measured data. All three sources were used with different source-shielding configurations.

Figure 2 shows the histograms created from the pulses generated by the Cf-252, Am-Be, and Am-Li neutron sources. In the measurements shown in Fig. 2, no shielding was used. For all three sources, very good separation of neutrons from gamma rays is observed. It is apparent that the Am-Be source provides the highest number of neutrons relative to gamma rays. On the contrary, the Am-Li source generates only a small number of detected neutrons with no shielding between the source and the detector. As a result, it is very difficult to obtain a statistically acceptable neutron pulse-height distribution for the identification of this source. Therefore, Pb shielding was later used for this source to eliminate the strong gamma-ray background. It should be noted that due to the low-energy particles from the Am-Li source, a higher pulse-height resolution was used in the measurement. This resolution is a factor of two higher than the resolution used for the two other sources. This change of resolution is reflected in Fig. 2 in the different position of the neutron and gamma-ray peaks for the Am-Li source.

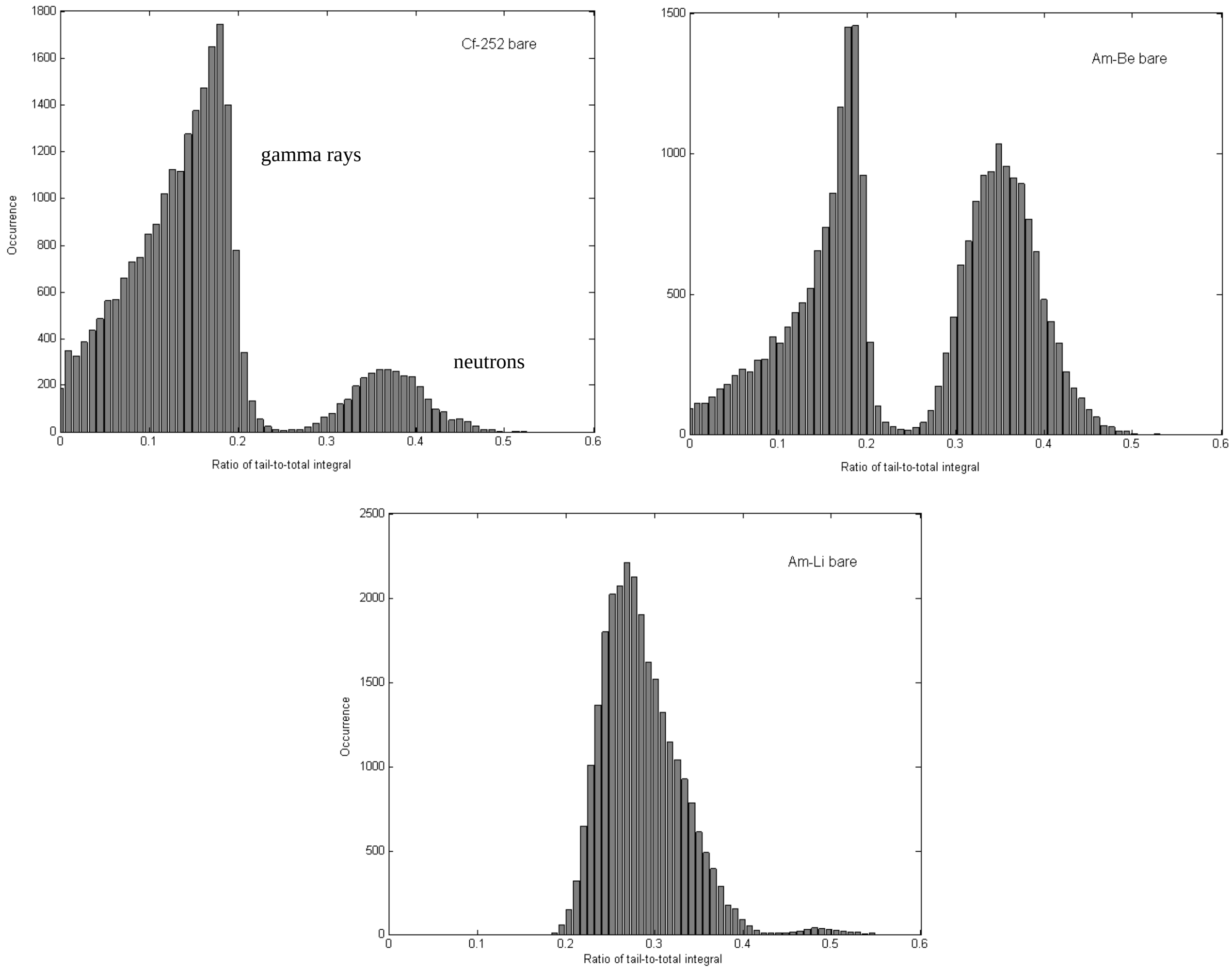

Figure 2. Histograms from the pulses generated by the Cf-252, Am-Be, and Am-Li sources.

Figure 3 shows the pulse tail integrals A_2 as a function of the total integrals A_1 of the pulses from the Cf-252, Am-Be, and Am-Li neutron sources. A very good separation of neutrons from gamma rays can be observed for all neutron sources. It also should be noted that the integral ranges differ as a consequence of the substantially different neutron spectra for these sources. The low number of the measured neutron pulses from the Am-Li source is clearly observable when compared to the number of the gamma-ray pulses.

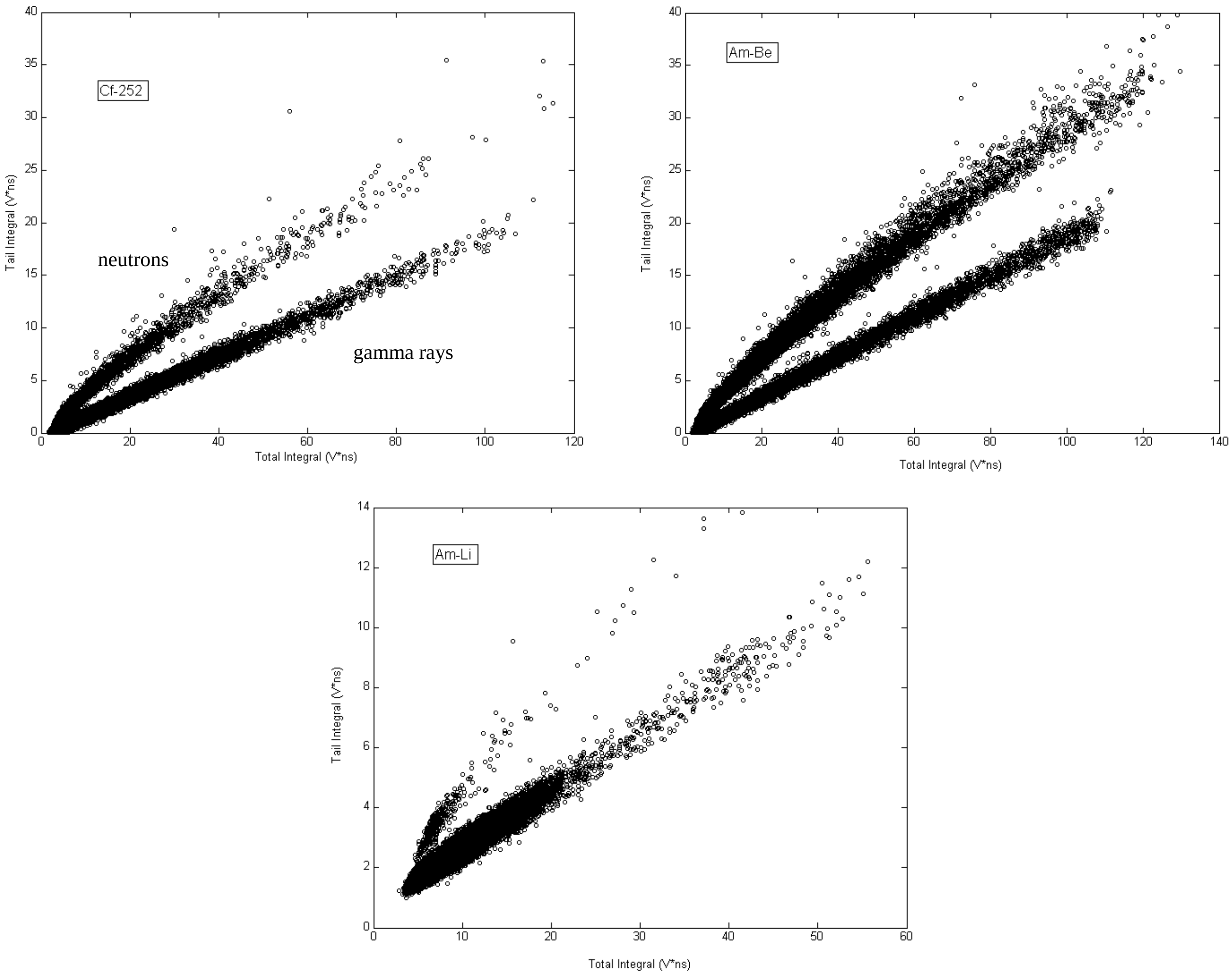

Figure 3. Tail integrals as a function of total integrals for the pulses acquired from the Cf-252, Am-Be, and Am-Li neutron sources.

Figure 4 shows a comparison of various detector-shielding configurations for the Cf-252 source, as well as the effect of Pb and PE shieldings on the performance of the PSD technique. The results are shown as a ratio of tail to total integral as a function of the pulse height. As expected, the presence of the Pb shield between the source and the detector causes the elimination of many of gamma rays, which results in a larger number of neutrons per acquisition than in the absence of shielding. No dramatic increase in the relative number of the neutron pulses is observed by transition from 1 in. of Pb to 3 in. of Pb. However, by using 3 in. of PE shielding, the number of neutrons decreases significantly as a result of neutron scattering and subsequent absorption.

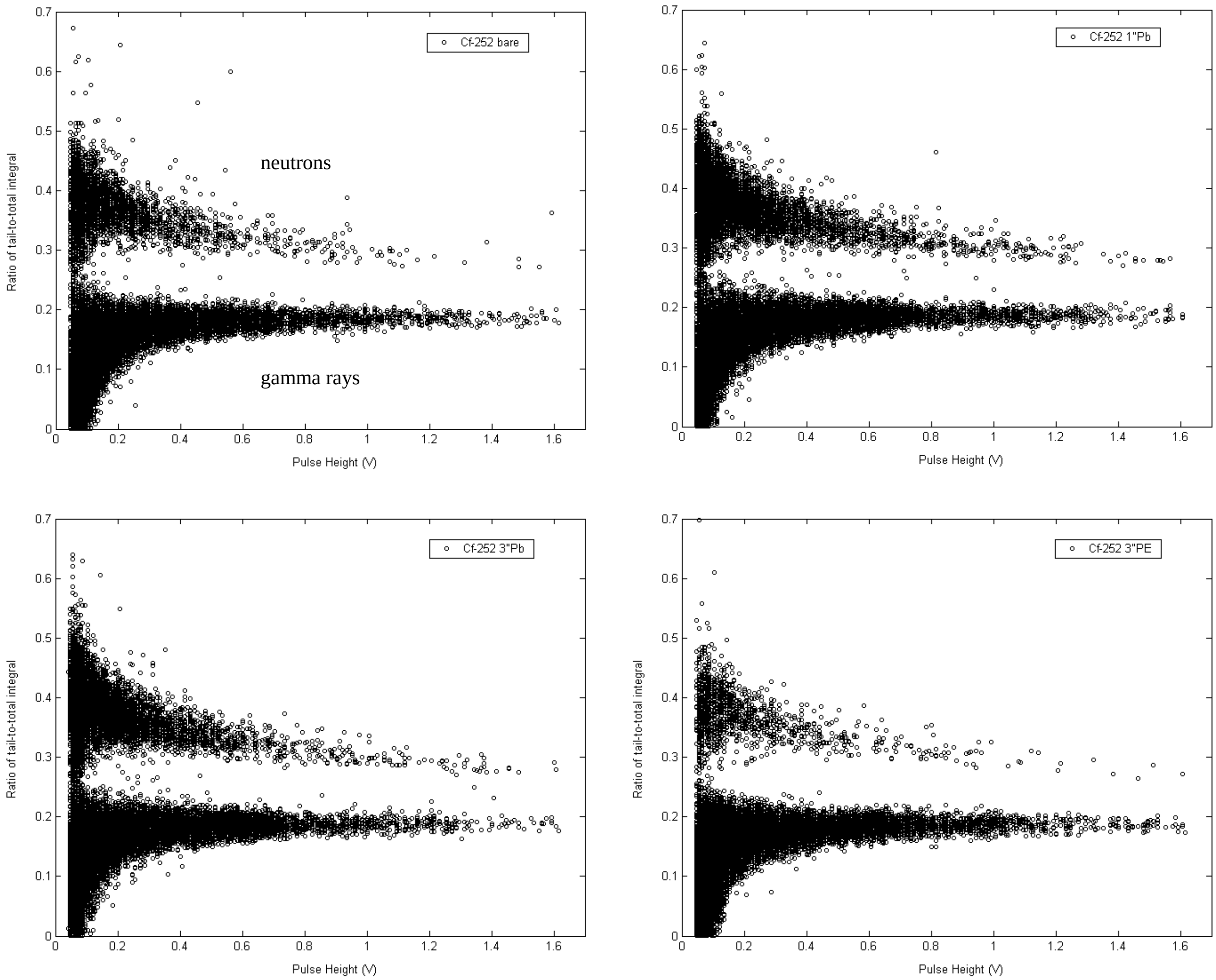

Figure 4. Various detector-shielding configurations for the Cf-252 source. The presence of lead and polyethylene alters the relative number of measured neutron and gamma-ray pulses.

3.2. Measurements Versus Simulations

Figure 5 shows a comparison of chosen simulated and measured pulse-height distributions for all three sources. The measurement points were interpolated to the simulation points and normalized to the area to allow direct comparison of the data. The measurement errors were calculated as the square roots of the measured data values. For the Cf-252 and the Am-Be source, the configurations with 1 in. of Pb and 1 in. of PE are shown. The configuration with 1 in. of PE is not shown for the Am-Li source because this configuration leads to a complete loss of neutron information. Instead, the configuration with 3 in. of Pb is shown. For Cf-252 and Am-Be, both configurations show excellent agreement. In cases of configurations with 1 in. of PE shielding, the measurement data exhibit slightly lower statistical accuracy than those with Pb shielding. This is due to the relatively lower number of neutrons in the data set.

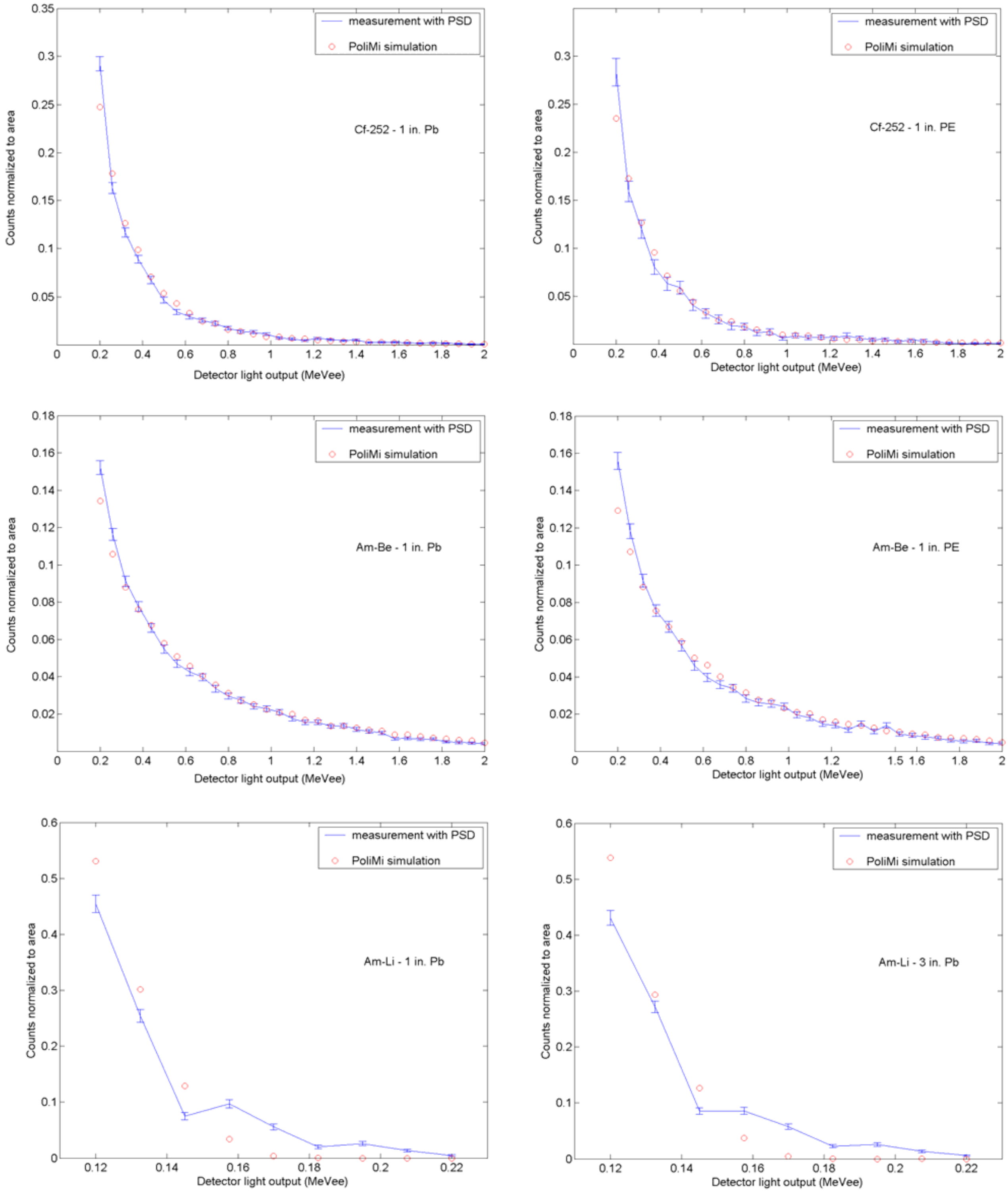

Figure 5. Comparison of measured and simulated pulse-height distributions for the Cf-252, Am-Be, and Am-Li sources for different source-shielding configurations.

For the Am-Li source, a relatively large difference is observed between the measurement and the simulation in Fig. 5. This difference is caused by a relatively low number of neutrons emitted from this source when compared to the number of gamma rays (see Fig. 3). As a result, it is very difficult to acquire enough accurate information to achieve a good agreement between the measured and simulated data. Because of the low average energy of the Am-Li neutrons, the influence of the measurement background on the data is enhanced, which can also alter the measured data.

3.3. Final Comparison of Measurement Results

Figure 6 shows the final comparison of the measured pulse-height distributions for all three sources and several source shielding configurations. It was observed that the general shape of the distributions is not significantly changed by the presence of the tested shields. However, the presence of PE increases the uncertainty of the measured data, especially at high light outputs.

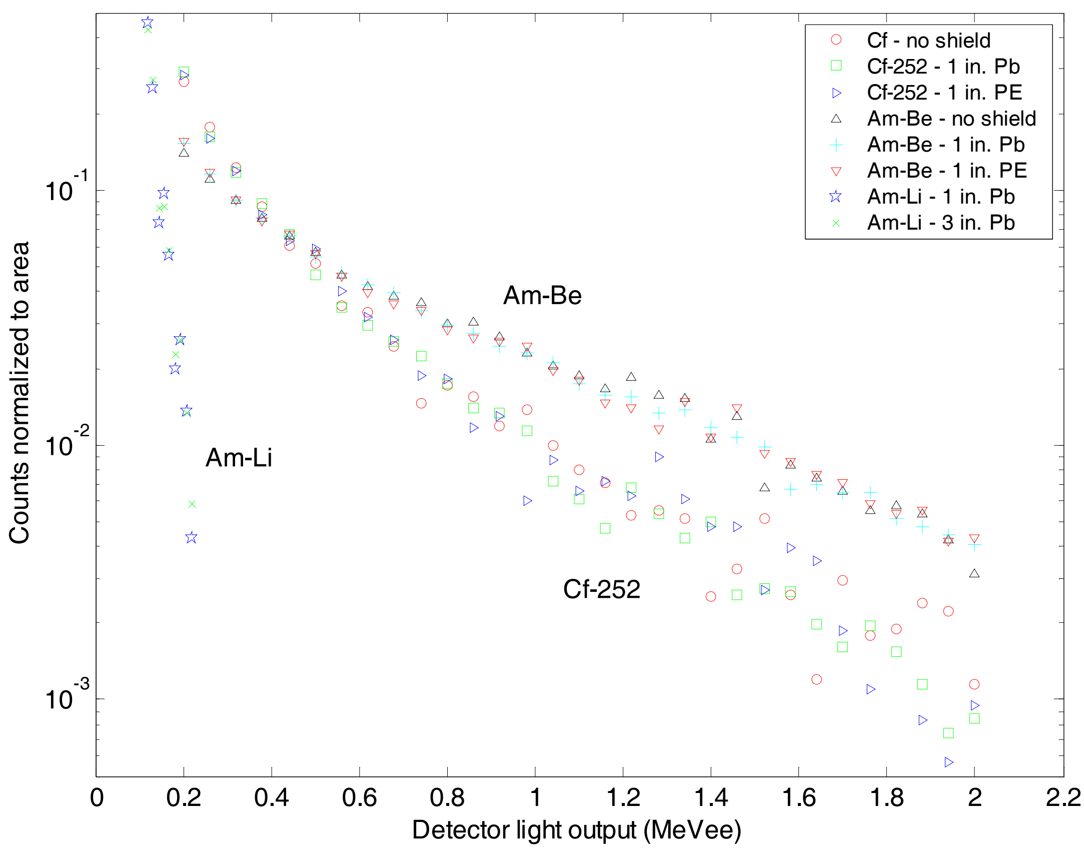

Figure 6. Comparison of measured pulse-height distributions for three neutron sources and different source-shielding configurations. The sources can be identified by the direct analysis of the distributions. Errors are not shown for clarity.

In Fig. 6, a clear distinction between the Cf-252 and the Am-Be source is observed. Below the light output value of 0.4 MeVee, statistical error plays only a minor role. Above this value, the general slope of the distributions can still be used for the source identification, even though statistical uncertainties are increased. The 1-in. PE block used for the Cf-252 source cause larger fluctuations of the measured distribution points when compared to other source-shielding configurations, especially above 1 MeVee. These fluctuations, however, still allow the identification of the sources. The Am-Li source produces neutrons with very low energy and thus can be easily distinguished from two other sources due to its low pulse-height distribution profile.

4. CONCLUSIONS

An existing technique has been applied to identify neutron sources in a fast and robust way based on the *direct analysis* of measured neutron pulse-height spectra using a liquid scintillator BC-501A and a fast Tektronix waveform digitizer TDS-5104. No subsequent neutron energy spectrum unfolding is required. An optimized digital PSD method was applied to pulses originating from various sources to obtain the pulse-height distributions. The measured pulse-height distributions were compared with distributions simulated with MCNP-PoliMi, and excellent agreement was achieved for the Cf-252 and Am-Be sources. For the Am-Li source, slightly less favorable results were obtained due to the relatively low number of neutrons emitted from this source when compared to the number of gamma rays, which resulted in increased statistical uncertainty in the measured neutron pulse-height distribution. The results show that the pulse-height distributions do not change significantly in the presence of the tested shields. Even in the presence of 1 in. of PE shielding, the Cf-252, Am-Be, and Am-Li sources can be easily distinguished. The presence of Pb, on the other hand, further improves the accuracy of the measured neutron pulse-height spectra by eliminating the gamma-ray background, which in turn improves the performance of the source identification technique.

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