Digital discrimination of neutrons and gamma-rays in liquid scintillators using wavelets

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A B S T R A C T

A novel algorithm for the digital discrimination of neutrons and gamma-rays in a mixed radiation field is presented. Most of the pulse shape discrimination methods in scintillation detection systems use time-domain features of the signal (e.g. charge comparison method or constant-time discrimination). However, there are no frequency-domain discrimination methods up to date in the literature. Our method employs the wavelet transform to extract frequency-domain features for discrimination. Compared to the pulse gradient analysis (PGA) algorithm, it provides an improvement in reducing the overlap area between neutron and gamma events and also in increasing the Figure of Merit (FoM). Another advantage of this method consists in the removal of the dependency of the discrimination method on timing features. Since the light output in the scintillation process is very noisy, this kind of dependency may degrade the performance of the algorithm.

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1. Introduction

Neutron spectroscopy has several applications in international safeguard, nuclear material control, and national security. More recently, neutron spectroscopy using organic scintillators has been used for tomographical imaging. Since organic scintillators are also sensitive to gamma-ray photons, a pulse shape discrimination (PSD) method between neutrons and gamma-rays is necessary.

Liquid scintillators are one of the most popular radiation detection materials because they can be shaped into the desired size for a specific application. Another advantage of using liquid scintillators is their excellent PSD properties and fast timing performance.

The liquid and plastics organic scintillators are synthesized to yield a molecular structure in which unbound π-electrons are prone to excitation by incident radiation. Such excitation can result in the promotion of π-electrons from the ground state \(S_0\) to one of several excited singlet states \(S_1, S_2, S_3\), etc. The eventual decay from such a state results in the emission of a photon which constitutes fluorescence and occurs a few nanoseconds after excitation. The intensity of the fluorescence of an organic scintillator decays exponentially [1]. An alternative decay path exists when an excited π-electron can undergo a spin reversal from the spin 0 singlet state to the spin 1 triplet state, resulting in a \(T_1 - S_0\) decay with the emission of light with a longer wavelength than fluorescence \(\text{(phosphorescence)}\) [1].

A π-electron in a \(T_1\) state may gain enough energy to return to the \(S_1\) state. This energy may be thermal or it is possible for two π-electrons in the \(T_1\) state to interact leaving one in the \(S_0\) state and one in the \(S_1\) state with the emission of photons [2]. The subsequent decay of the \(S_1\) electron emits light called delayed fluorescence which has the same characteristics as the fluorescence except that the intensity does not decay exponentially [3].

Since the triplet density is determined by the rate of energy loss of the incident particle, heavier particles show greater energy loss rate and produce delayed fluorescence yielding output pulses that decay more slowly than those from lighter particles. The difference between the pulse shapes arising from the interaction of heavy particles in scintillation and those stemming from the interaction of light particles and photons has been exploited in PSD and allows the determination of the radiation type.

There exist different PSD methods reported in the literature. The most popular methods are the Charge Comparison (CC) method and the zero-crossing method. These methods have been implemented both in analog and in digital systems. The CC method [4] was based on the work of Jordanov and Knoll [5] and was based on the comparison between the integrations of the signal over two different intervals, one the entire pulse and the other only the tail. The ratio of these two integrations is used as the separation parameter [6]. In zero-crossing method, the input signal is first integrated and then differentiated. The discrimination value is the delay between the start signal...
and the time at which the differentiated signal crosses the zero line [7].

The development of fast analog to digital converters and the use of digital processors allows for the implementation of analog methods on FPGA (field programmable gate array) technology and also applying the new digital signal processing methods for PSD. Barton et al. [8] digitally implemented the optimal filter for PSD which was described by Gatti [9] nearly forty years ago. In Ref. [6], the Gatti’s optimum filter method was implemented to discriminate between alpha and beta particles in liquid scintillators. The Gatti’s method was based on calculating a G parameter which was positive for alpha particles and negative for beta signals. This parameter showed the likelihood of a new signal to have been produced by and alpha or beta excitation.

D’Mellow et al. [10] proposed a fast and real-time algorithm based on using Pulse Gradient Analysis (PGA) to discriminate between neutrons and gamma-rays in liquid scintillators. Their method showed a better discrimination performance compared to the CC method. Aspinall et al. [11] verified the discrimination of neutron and gamma-ray events in an organic scintillator with the PGA method by comparing the results of the PGA method with those of the Time of Flight (TOF) measurement. The discrimination performance of the PGA algorithm was observed to be consistent with that achieved by the TOF.

Most of the existing PSD methods for scintillation detection systems employ time-domain features of the signal to discriminate between pulse shapes. However, there are no contributions to date regarding PSD methods operating in the frequency domain. Since the pulse shapes produced at the output of a scintillator are non-stationary signals, their analysis using conventional Fourier transform cannot capture their most relevant features. The wavelet transform is an efficient tool to analyze non-stationary signals on a time–frequency scale [12,13].

In this paper, we propose a new PSD method based on the wavelet transform which is able to detect neutrons and gamma-rays in liquid scintillators. Compared to time-domain methods, this technique is more robust to noise and abrupt changes in the pulse waveform and can be used as a reliable method in digital spectroscopy. The performance of the wavelet method is compared with that of the PGA. The experimental results show that the wavelet-based PSD method has a better performance compared to the PGA algorithm.

2. Experimental set-up

The experimental setup of the scintillator and source is shown in Fig. 1. An americium–beryllium (Am/Be) source was exposed to a small-volume (4.5 ml) liquid scintillator (John Caunt Scientific Ltd., Oxon, UK) filled with EJ-301, optically coupled to a fast photomultiplier tube (PMT). The output signal of the PMT was sampled using a fast digitizing oscilloscope (Agilent Technologies Inc.) at a sampling rate of 4 GSPS with a 10-bit amplitude resolution. Data were collected using four different experimental configurations as described in Table 1 and were transmitted to the host computer for further processing. A lead shield with a thickness of 50 mm was used to attenuate the gamma-ray component of the field. The neutron flux was attenuated by moving the source to the back of the tank or through the use of a polyethylene sphere with an external diameter of 208 mm and an internal diameter of 63 mm [10]. Although the main use of Am/Be sources is usually in the production of neutrons, an associated gamma-ray yield is inevitably produced after the α-decay of the americium component and also as the result of inelastic neutron scattering in the surroundings. In addition, the gamma-ray in the background is also present during the experiment. Therefore, the Am–Be source can be used as a mixed field of neutrons and gamma rays.

3. Feature extraction

3.1. The wavelet transform

The wavelet transform decomposes signals over dilated and translated wavelets. The wavelet transform of a function $f \in L^2(\mathbb{R})$, the space of square integrable functions over $\mathbb{R}$, at scale $a$ and shift $b$, is defined as

\[
W_f(a, b) = \langle f, \psi_{a,b} \rangle = \int_{-\infty}^{\infty} f(t) \frac{1}{\sqrt{a}} \varphi^* \left( \frac{t-b}{a} \right) \, dt
\]  

where $\varphi \in L^2(\mathbb{R})$ is the wavelet function with zero average and unit $L_2$ norm $\| \varphi \| = 1$. In this application, ‘Haar’ wavelets [14] were used. It should be noted that each pulse is normalized to a unit peak to peak signal before computing the wavelet transform. The normalization process removes the dependency of the wavelet transform on the amplitude of the pulse.

3.2. Feature selection

A new function $P(a)$ called the ‘Scale Function’ is defined in this paper as the energy of the wavelet transform of the signal at a specific scale and with different shifts. $P(a)$ is defined as

\[
P(a) = \frac{1}{1 + n_b \sum_{j=0}^{n_b} |W^j_f(a, b)|^2}.
\]  

Typical neutron and gamma waveforms with their corresponding scale functions are plotted in Fig. 2. It can be observed that the scale function provides a good separation between neutron and gamma pulses. The scale functions of 50 normalized pulses captured from a mixed neutron/gamma field are plotted in Fig. 3. For implementation simplicity, the values of the scale function at
scales 512 and 1024 are selected as the discrimination parameters. These scales are chosen as powers of 2 to use the discrete wavelet transform (DWT). The DWT can be easily implemented in digital processors and FPGAs [15]. The optimum features are selected using the following equations:

\[ f_1 = P(a)|_{a=512} \] (3)

and

\[ f_2 = \frac{P(a)|_{a=1024}}{P(a)|_{a=512}}. \] (4)

4. Experimental results

To verify the performance of the algorithm, the wavelet method was applied to the data from the four configurations reported in Table 1 where gamma and neutron events are counted. For the first configuration, the scatter plot and the experimental distribution are plotted in Figs. 4 and 5, respectively. For the experimental distribution plot, the x-axis (discrimination value) is the second feature \( (f_2) \). Although this feature is not the only discrimination value in the wavelet method, it can be used as a good parameter to visualize the estimated distribution of neutrons and gamma rays and provides a very good separation of the two sets. The sum of two Gaussian functions is fitted to the histogram representing the distribution of neutron and gamma events.

Fig. 4 shows the scatter plot and Fig. 5 shows the experimental distribution for the data collected with the first configuration with no additional shielding. With this configuration, the desired field consists of mostly gamma rays and some neutrons. During this experiment, 734 pulses were captured: 228 pulses were classified as neutrons and 506 pulses as gamma rays and the resulting
The overall results are compared with those obtained with the PGA algorithm. Table 2 shows the neutron and gamma-ray counts and estimated neutron/gamma ratios derived from the scatter plots for the PGA algorithm and for the wavelet method for different configurations. Also, Table 3 shows the fractional areas bounded by the Gaussian fits to the neutron and gamma-ray peaks and estimated neutron/gamma ratios for the experimental distribution. The fractional and the overlap areas are calculated using the fitted Gaussian plots to the experimental distribution. The overlap fractional areas are the integral under the curve of two Gaussian curves fitted to the neutron and gamma events. The gamma fractional area is defined by the overlap fractional areas divided by the integral under the curve of the Gaussian curve fitted to the gamma event. The overlap areas have been substituted from the gamma and neutron areas. The neutron/gamma ratio was 0.45. Table 2 shows the experimental results for the other configurations already explained in Table 1.

The separation of neutron and gamma events was carried out by defining hard-threshold boundaries on the feature plot. These boundaries were defined such that the neutron/gamma ratio of the configuration 3 in the Table 1 becomes approximately 1. However, there were few events between the two populations on features plot which can be ascribed equally to gammas or neutrons and cannot be separated using this method. The events were classified as neutron if \((0.5 < f_1 < 2 \text{ and } f_2 > 1.15)\) or \((f_1 > 2 \text{ and } f_2 > 1.2)\). The other events which did not fall in the neutron boundaries were classified as gamma and their pulse shape demonstrated a very short decay time which verified this classification. The events with small values of \(f_1\) were observed to have low amplitude and are most likely to be spurious pulses and are considered as noise. These events were not observed by setting a lower trigger.

The results obtained in Table 2 with the wavelet method and the PGA algorithm applied to the data from the configurations in Table 1 show similar performance. However, the fractional areas in Table 3 show that the wavelet method has an improved performance compared to the PGA algorithm and that the overlap areas between the neutron and gamma events have dramatically been decreased. Compared to the PGA algorithm, the overlap between neutron and gamma events has decreased 76.8% on average.

Another advantage of the wavelet method over the PGA algorithm consists in using two features which allow a better separation between the possible cases. The discrimination between the gamma and neutron events in the wavelet method is obtained by defining simple boundaries, which makes the separation easier compared to the nonlinear discriminator line of the PGA method.

Most of the time-domain methods use samples of the signal at a specific time or ratio with respect to the peak time and amplitude. Therefore, feature selection is very sensitive to noise and variations of the light intensity. The frequency domain analysis allows for studying the signal at a specific frequency. The scale value in the wavelet transform of the signal has an inverse relationship with the frequency value. Since the features are extracted at scales 512 and 1024 which are related to two low frequency components, the discrimination algorithm is less sensitive to noise.

![Fig. 5. The experimental distribution of configuration 1.](image)

### Table 2

<table>
<thead>
<tr>
<th>Method</th>
<th>PGA algorithm</th>
<th>Wavelet method</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Gamma</td>
<td>Neutron</td>
</tr>
<tr>
<td>1</td>
<td>490</td>
<td>237</td>
</tr>
<tr>
<td>2</td>
<td>859</td>
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<td>1234</td>
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<td>4</td>
<td>1612</td>
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### Table 3

<table>
<thead>
<tr>
<th>Method</th>
<th>PGA algorithm</th>
<th>Wavelet method</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Gamma</td>
<td>Neutron</td>
</tr>
<tr>
<td>1</td>
<td>0.686</td>
<td>0.303</td>
</tr>
<tr>
<td>2</td>
<td>0.816</td>
<td>0.168</td>
</tr>
<tr>
<td>3</td>
<td>0.515</td>
<td>0.476</td>
</tr>
<tr>
<td>4</td>
<td>0.758</td>
<td>0.225</td>
</tr>
</tbody>
</table>

All fractional areas were measured with an uncertainty of ± 0.001.

5. Discussion

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sensitive to high frequency additive noise which is present in the frequency spectrum of pulses.

A comparison between our technique and the PGA algorithm can be done by using the Figure of Merit (FoM) for the neutron/gamma discrimination defined as

\[
\text{FoM} = \frac{S}{\text{FWHM}_n + \text{FWHM}_g} \tag{5}
\]

where \(S\) is the separation between the peaks of the two events, \(\text{FWHM}_n\) is the full-width half-maximum (FWHM) of the spread of events classified as gamma-rays and \(\text{FWHM}_g\) is the FWHM of the spread in the neutron peak [10]. The comparison between the FoMs of the wavelet method and the PGA algorithm is reported in Table 4, confirming the improved discrimination. It can be observed that FOMs are different for different configurations. It can be due to the difference in the average energies of detected gamma and neutron events resulting from the use of different shield combinations.

A procedure similar to that presented in this paper can be applied to other scintillation detection systems where the decay characteristics of the pulse shapes are used for PSD in radiation spectroscopy and measurement [16]. The discrimination method presented in this paper can also be used in the applications which use scintillator detectors and require PSD such as cancer diagnosis and treatment, biomedical imaging, home-land security, nuclear non-proliferation, and worker safety.

### Table 4
Comparison between the FoM of the PGA algorithm and wavelet method

<table>
<thead>
<tr>
<th>Configuration</th>
<th>PGA algorithm</th>
<th>Wavelet method</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
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</tr>
<tr>
<td>2</td>
<td>0.82</td>
<td>1.68</td>
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<tr>
<td>3</td>
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<td>1.64</td>
</tr>
<tr>
<td>4</td>
<td>0.83</td>
<td>1.49</td>
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References