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An algorithm for charge-integration, pulse-shape discrimination and estimation of neutron/photon misclassification in organic scintillators

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ABSTRACT

Organic scintillators are frequently used for measurements that require sensitivity to both photons and fast neutrons because of their pulse shape discrimination capabilities. In these measurement scenarios, particle identification is commonly handled using the charge-integration pulse shape discrimination method. This method works particularly well for high-energy depositions, but is prone to misclassification for relatively low-energy depositions. A novel algorithm has been developed for automatically performing charge-integration pulse shape discrimination in a consistent and repeatable manner. The algorithm is able to estimate the photon and neutron misclassification corresponding to the calculated discrimination parameters, and is capable of doing so using only the information measured by a single organic scintillator. This paper describes the algorithm and assesses its performance by comparing algorithm-estimated misclassification to values computed via a more traditional time-of-flight estimation. A single data set was processed using four different low-energy thresholds: 40, 60, 90, and 120 keVee. Overall, the results compared well between the two methods; in most cases, the algorithm-estimated values fell within the uncertainties of the TOF-estimated values.

1. Introduction

The accurate detection of neutrons is important in many fields including nuclear safeguards and security, reactor instrumentation, particle physics, material science, dosimetry, and astrophysics [1]. Organic scintillators are a good candidate for neutron measurement systems due to their sensitivity to fast neutrons and their pulse shape discrimination (PSD) properties, which allow for reasonably accurate identification of detected particle type [2–4]. The PSD performance of organic scintillators also makes them especially useful for applications in which simultaneous detection of neutrons and photons is desirable [5,6].

Several PSD methods exist, but the charge-integration method is frequently used due to its simplicity and performance [7–10]. In particular, the charge-integration method allows for highly accurate discrimination between photons and neutrons at high-energy depositions. However, at low-energy depositions (below ~1 MeV neutron energy deposited), discriminating between photons and neutrons becomes increasingly difficult and eventually particle misclassification becomes unavoidable. In certain applications, such as the measurement of special nuclear material (SNM), measured data often include a large number of low-energy depositions. To properly analyze these low-energy depositions, it is important to accurately estimate the extent of particle misclassification.

PSD misclassification has been evaluated previously by using information gained from time-of-flight (TOF) measurements [11]. The large difference in the velocity of photons and neutrons allows for a particle to be classified based on the time between its emission and subsequent detection. The TOF classifications can be used as a reference to assess the performance of a PSD method. However, particle TOF can only be obtained through specific experimental setups that are impractical or impossible to utilize in the uncontrolled environments often found in field measurements. As such, it is advantageous to develop methods that are capable of evaluating PSD performance while making use of readily available information.

An algorithm was developed that is capable of automatically performing charge-integration pulse shape discrimination (CIPSD) in a methodical and consistent manner. This algorithm is also capable of estimating the fraction of misclassified photons and neutrons while using only the information measured by a single scintillator cell. The algorithm has been wrapped into a fully functional MATLAB graphical user interface (GUI) called "Auto Slice

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PSD", and has been successfully used in several studies [12–14]. The GUI is capable of loading and processing measured data sets of various formats. The data can be visualized in various ways before and after data processing and the user has the option to save an image at any point. After processing, relevant information on particle discrimination and misclassification is provided to the user with the option to save a detailed report.

This paper will give a detailed description of the algorithm utilized in Auto Slice PSD and will assess its ability to estimate photon and neutron misclassification in the absence of TOF information. The discussion will begin with an overview of the CIPSD method. This overview will be followed by an in-depth description of the four main components of the algorithm. The acquisition and processing of the TOF-tagged data set used for assessing the performance of the algorithm will be subsequently discussed. Finally, Auto-Slice-PSD-estimated photon and neutron misclassification values will be presented for comparison to TOF-estimated values. This comparison will be made in light of the known statistical and systematic uncertainties associated with the TOF methodology, and conclusions will be drawn on the relative accuracy of the Auto Slice PSD algorithm.

2. Charge-integration pulse-shape-discrimination

The algorithm utilized in Auto Slice PSD is based on the CIPSD principle. In CIPSD, particles are identified based on the fraction of pulse that falls within the "tail" region of the pulse. This fraction is dictated by the amount of phosphorescent and delayed fluorescent light produced, which is dependent on the density of triplet states induced along the charged-particle interaction path [1]. Heavier charged particles will produce a higher density of triplet states because they exhibit a higher rate of energy loss, dE/dx [1]. For equivalent energy depositions, recoil protons resulting from neutron interactions will induce a larger tail (slow) component than recoil electrons resulting from photon interactions [1]. In CIPSD, a pulse is integrated over two regions to determine the fraction of the pulse that occurs in the tail. The first region includes the entire pulse and, for fast organic scintillators, typically ranges from several nanoseconds prior to the peak of the pulse to several hundred nanoseconds after the peak of the pulse [15]. The integral of this region is referred to as the "total integral". The second region includes only the tail portion of the pulse and, for fast organic scintillators, typically begins several nanoseconds after the pulse maximum and extends to the same time as the total integral region [15]. The integral of this region will be referred to as the "tail integral". The definition of the integration regions is important to the overall performance of the CIPSD method and should be optimized for the detector being used [15].

With the computed tail and total integrals, it is possible to generate a scatter plot of pulses on the tail-integral-vs.-total-integral axes. This scatter plot will show two clusters, as seen in Fig. 1. The points in the upper cluster signify pulses with a higher relative fraction of light in the tail region and represent pulses from heavier particles. Conversely, the points in the lower cluster represent pulses with a lower relative fraction of light in the tail region. Throughout this paper, it will be assumed that the upper cluster contains pulses from neutron interactions and the lower cluster contains pulses from photon interactions. A curve (or line) can be created that divides the neutron and photon cluster; this curve will be referred to as a "discrimination curve". It is possible to discriminate between pulses resulting from different particle interactions by designating pulses that fall above the discrimination curve to be coming from neutron interactions and pulses below the discrimination curve to be coming from photon interactions.

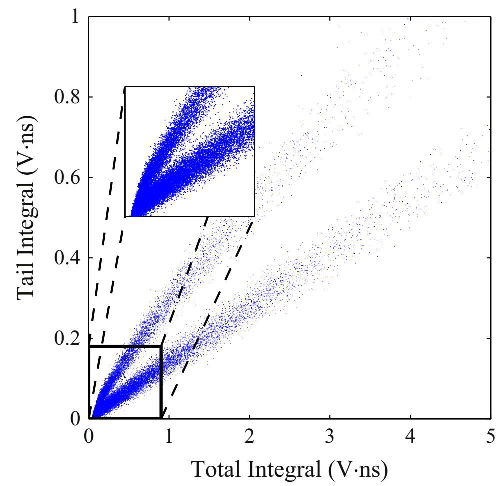

Fig. 1. Typical tail-integral-vs.-total-integral scatter plot resulting from the CIPSD method applied to Cf-252 data. Inset emphasizes cluster overlap at the low-energy-deposition region. Pulses were collected with an EJ-309 organic-liquid scintillator and processed using a 30-keVee measurement-threshold. Data are available out to approximately 9 V · ns in total integral and 1.8 V · ns in tail integral but are not shown due to the relative sparsity at these higher energy depositions. It should be noted that the data set shown here differs from the data set that will be described in Section 4.

Ideally, the neutron and photon clusters would be fully separated and allow for straightforward discrimination. However, at low total-integral values, which correspond to small energy deposition (below ~1 MeV neutron energy deposited), the clusters begin to overlap. This overlap is emphasized in the inset of Fig. 1. Cluster overlap is undesirable because it results in misclassification when using a discrimination curve for particle identification. The degree to which the clusters overlap can be reduced and practically completely removed by increasing the measurement threshold. However, increasing the measurement threshold will always result in a loss of low-energy information. While using a discrimination curve with cluster overlap will always result in some amount of misclassification, it is reasonable to assume that in some applications there is an acceptable level of misclassification that can be tolerated in order to retain the low-energy information. The algorithm described in this paper is intended for use in such applications. The algorithm attempts to minimize the number of misclassified particles, subject to a set of user-defined parameters, and estimates the particle misclassification resulting from the calculated discrimination curve. This estimation is performed using only the information measured by a single organic scintillator.

3. Auto Slice PSD algorithm

Auto Slice PSD determines a discrimination curve by using a multi-step process that includes slicing the data into smaller subsets, fitting the distribution of tail-to-total-integral ratios in each slice, and using the fits to find the optimal discrimination points that minimize misclassification in each slice. Once identified, these points can be used to fit a discrimination curve through the data set. Additionally, by analyzing the slice-by-slice fits it is possible to estimate the fraction of neutrons and photons misclassified by the discrimination curve.

3.1. Slicing the data

The first step in determining a discrimination curve is to divide the full data set into smaller subsets by using linear slices. By