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Application of Bayes' theorem for pulse shape discrimination

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ABSTRACT

A Bayesian approach is proposed for pulse shape discrimination of photons and neutrons in liquid organic scinitillators. Instead of drawing a decision boundary, each pulse is assigned a photon or neutron confidence probability. This allows for photon and neutron classification on an event-by-event basis. The sum of those confidence probabilities is used to estimate the number of photon and neutron instances in the data. An iterative scheme, similar to an expectation-maximization algorithm for Gaussian mixtures, is used to infer the ratio of photons-to-neutrons in each measurement. Therefore, the probability space adapts to data with varying photon-to-neutron ratios. A time-correlated measurement of Am–Be and separate measurements of ^{137}Cs, ^{60}Co and ^{232}Th photon sources were used to construct libraries of neutrons and photons. These libraries were then used to produce synthetic data sets with varying ratios of photons-to-neutrons. Probability weighted method that we implemented was found to maintain neutron acceptance rate of up to 90% up to photon-to-neutron ratio of 2000, and performed 9% better than the decision boundary approach. Furthermore, the iterative approach appropriately changed the probability space with an increasing number of photons which kept the neutron population estimate from unrealistically increasing.

1. Introduction

1.1. Overview of the PSD problem

In organic scintillators the fraction of light emitted during delayed fluorescence depends on the exciting particle, therefore it is possible to differentiate between neutron and photon interactions through pulse shape discrimination (PSD) [1]. Although this property has been known for decades, recent advancements in pulse digitization [2] and the demand for an alternative to the ^{3}He neutron detectors for security applications [3] have invigorated the interest in PSD performance in organic scintillators. Reliable and robust PSD methods are necessary with organic scintillators to match the gamma rejection capabilities of ^{3}He detectors.

The charge integration PSD method, in both analog and digital applications, relies on the ratio of pulse tail to total integrals [4]. This PSD parameter is widely used in gauging PSD performance in organic scintillators [5–7]. There are other methods for quantifying PSD parameters [8], all of which provide a way of clustering neutrons and photons in a particular two dimensional space. Typically one dimension of this space is the PSD parameter, and the other is some metric of energy deposition such as pulse height or pulse integral. A well-chosen PSD parameter ensures adequate separation between photon and neutron populations. The width of the photon and neutron distributions is inversely proportional to deposited energy, which makes classification difficult at lower energies. In this paper we apply a low threshold of 25 keVee ("kilo-electron Volt electron equivalent"), equivalent to estimated 245 keV neutron deposited energy.

1.2. New classification method

In this work we present a new classification methodology which departs from typical approaches of drawing the optimal decision boundary between photon and neutron distributions [9,10]. In our methodology, instead of segregating pulses into distinct groups, each pulse is assigned a neutron and photon weight based on posterior probability calculated from Bayes' theorem using the photon-to-neutron ratio as the prior probability as will be discussed in Section 3.2. The posterior probabilities are then used to estimate a new prior, and the process repeats until a convergence criteria is met. This iterative scheme successfully adapts the probability space to different proportions of neutrons and photons in the measured data. Furthermore, the sum of posterior probabilities is shown to be a better estimator of total instances of photons and neutrons than an optimal decision boundary that minimizes misclassifications. For our two class problem, the decision boundary that minimizes misclassification

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is set at a line where posterior probability equals 50%. Events with a PSD parameter above this boundary are classified as neutrons and below as photons.

Performance of the PSD method in this paper was quantified from a neutron detection point of view. Any effective PSD method has to simultaneously maintain high neutron efficiency and a high photon rejection rate [11]. Photon data sets were taken from measurements of pure photon sources, and neutrons from a time correlated measurement of an Am–Be source. Photon and neutron pulse data were combined to form synthetic data sets with varying photon-to-neutron ratios. Neutron efficiency was calculated as a function of this ratio by summing posterior probabilities, we define this as the probability weighted method. This was then compared to neutron efficiency obtained by discrimination using a decision boundary.

2. Experiment

Multiple measurements were performed with the same experimental setup to benchmark the new Bayesian PSD method. An Am–Be source was measured to provide a data set of time tagged neutrons. Three photon sources, ^{137}Cs, ^{60}Co and ^{232}Th, were measured separately to provide the corresponding set of pure photon pulses. The photon and neutron data sets were combined to produce mixed data sets with desired photon-to-neutron ratios.

This approach was favored over combined measurement of neutron and photon radiation sources for two reasons. First, direct measurement of high photon-to-neutron ratio would necessitate high count rates, which introduces complications from incomplete double pulse rejection. Double pulses are readily characterized as neutron pulses, and their inclusion perturbs the metrics used to quantify PSD performance. Secondly, synthetically adding in photon pulses into the mixed data sets gives us greater control in the choice of a photon-to-neutron ratio. Finally, uncertainties associated with the detector–source geometry and source strength, which would be included if mixed radiation fields were measured directly, are precluded from the estimation of photon-to-neutron ratio when data sets are mixed after measurements.

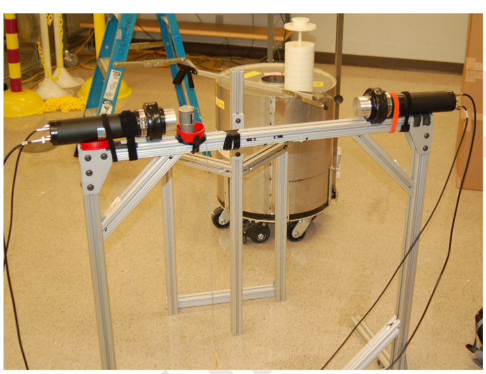

Fig. 1. Setup of the two detectors with Am–Be source in position.

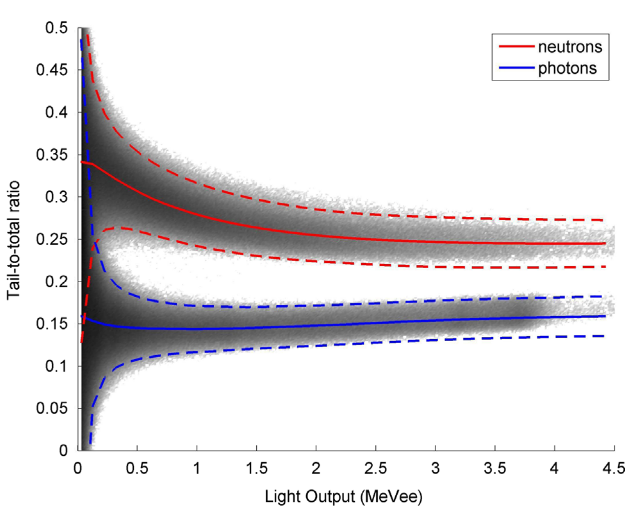

Fig. 2. The mean (solid lines) and three standard deviation (dashed lines) fits as applied to the Am–Be data set.

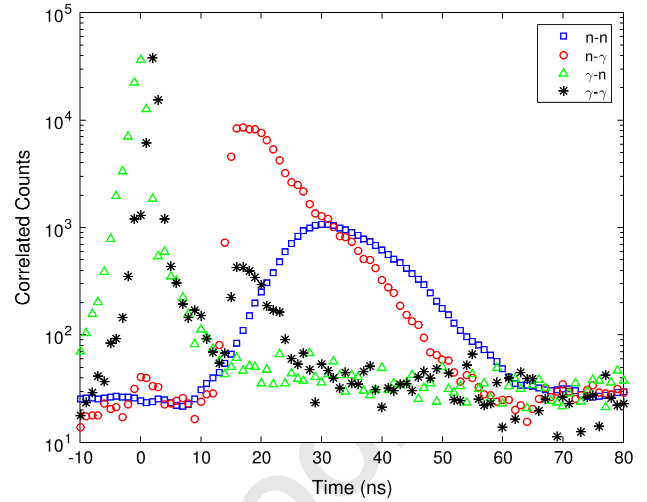

Fig. 3. Timing distribution of correlated counts between two liquid scintillator detectors using and Am–Be source. The minimum correlation probability threshold was 99% to minimize appearance of misclassified correlations.

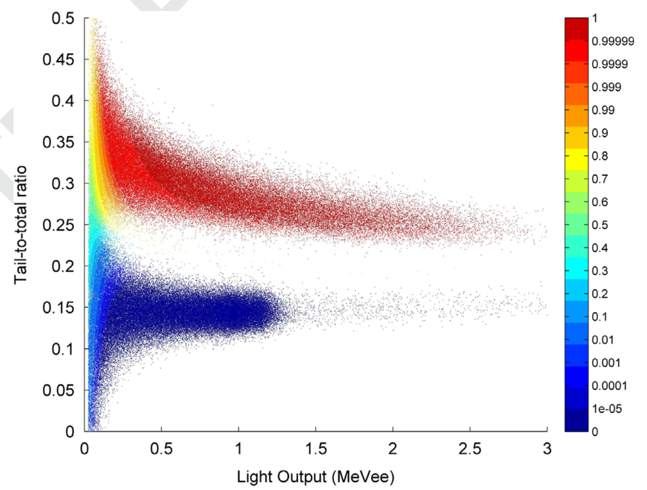

Fig. 4. The distribution of neutron posterior probabilities for 1:1 mixture of ^{60}Co and time tagged neutron data.

2.1. Setup and detector settings

Two 2 × 2 in. EJ-309 organic liquid scintillators coupled to Hamamatsu H1949-50 photomultiplier tubes (PMT) were used for the measurements. Full waveforms were digitized with a CAEN DT5720, 12-bit, 250 MHz digitizer which were saved on a computer through a USB cable. For the Am–Be measurement, one detector was positioned approximately 49.5 cm from the source and was used to benchmark the PSD method; a second detector was positioned approximately 0.5 cm from the source and was used to time tag correlated fast neutrons and high energy gammas originating in the (α,n) reaction [12]. The biases applied on the

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