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Measurement of neutrons down to 200 keV with pulse shape discrimination using an EJ-301 liquid scintillator

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ABSTRACT

Pulse shape discrimination is a method commonly used to separate gamma and neutron signals in liquid scintillation detectors. The method works well for neutrons above 500 keV, but as the energy deposited in the detector decreases, so does the effectiveness. In order to utilize pulse shape discrimination capabilities at lower energies, a 1.27 cm thick EJ-301 detector operated at a bias voltage of 2200 V has been used. The detector has been shown to have an average misclassification of 0.5% of gamma pulses over the total energy range from 35 keVee to 400 keVee, and 2.0% in the most sensitive region from 35 keVee to 45 keVee. A measurement performed using the time-of-flight method at the Gaerttner Linear Accelerator Facility at Rensselaer Polytechnic Institute has shown that with the pulse shape discrimination method, this detector can detect and characterize neutron pulses down to 200 keV.

1. Introduction

Detection of keV-energy neutrons is important in the measurement of fission and neutron scattering data, nuclear nonproliferation and interrogation analysis of nuclear material. These measurements are often accompanied by a high gamma background, and a method of discrimination between the neutron and gamma interactions is necessary. At thermal and epithermal energies, detectors can take advantage of the large energy release of nuclear reactions such as the ^{10}B and ^{6}Li(n,α) reactions. However, these detectors suffer from low efficiency at higher energies. The neutron detection efficiency of a 9 mm thick Li glass detector peaks at 6% around 250 keV [1] which is the peak of the ^{6}Li resonance. Liquid scintillation detectors can have much greater efficiencies in the keV region and a similar sized EJ-301 detector has a neutron detection efficiency of approximately 53% at 250 keV. This increase in neutron detection efficiency makes EJ-301 a desirable detector in this energy range; however, liquid scintillators also have a high gamma detection efficiency and these gammas must be discriminated against in order to achieve a usable measurement. Pulse shape discrimination (PSD) techniques have been extensively developed and demonstrated for neutron energies above 500 keV [2], but difficulties exist in extending pulse shape discrimination below this threshold. As the neutron energy decreases, the probability of gamma rays being falsely classified as neutrons, which is referred to as the gamma misclassification rate, also increases.

A common method for testing PSD is to calculate a PSD parameter for each pulse based on the difference between the long and short charge integrations. A figure of merit is then calculated by dividing the separation between the gamma parameter distribution and the neutron parameter distribution by the widths of these distributions. Many PSD studies with EJ-301 detectors focus on this figure of merit and do not present results for pulse classification accuracy [3,4]. One study comparing four different PSD methods did present the rate of correct neutron pulse identification, but did not test their gamma misclassification rates [5]. However, similar work has been performed on EJ-309 detectors, using reference pulse shapes for energy deposition below 70 keVee [6]. That method was shown to classify neutrons down to 200 keV, and have a 5% misclassification rate of gammas between 35 and 45 keVee [6]. In this work we are focusing on reducing this misclassification rate using an EJ-301 detector and validating the minimal detectable neutron energy through time-of-flight measurements. This work attempts to improve keV-energy neutron detection by using a 1.27 cm thick EJ-301 detector operated at high bias voltage reduce this misclassification rate and validate the minimal detectable neutron energy through time-of-flight measurements by presenting misclassification rates as a function of energy.

The physics behind PSD relies on the fact that neutrons and gamma rays will deposit their energy in different ways in the scintillation material causing distinct pulse shapes. X-rays and gammas interact primarily

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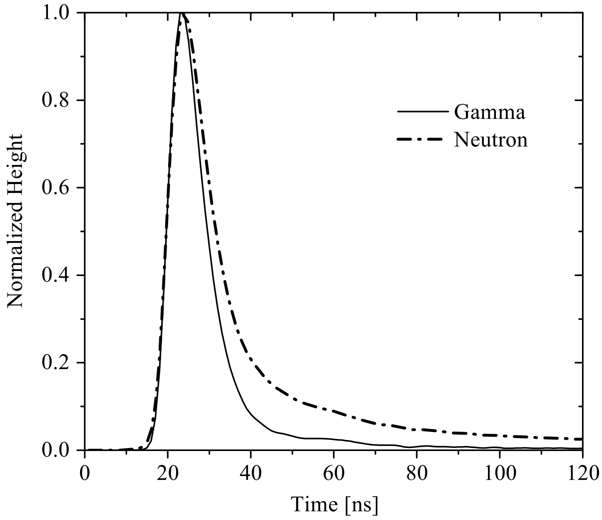

Fig. 1. Average normalized pulse shapes obtained from gammas interactions and from neutron interactions. It can be seen that the two shapes have very similar rise times, but disparate fall times, caused by the neutron exciting longer lived states. Unknown pulses were characterized based on channels 40 through 60 ns, as this was the area of largest difference between the two pulse shapes.

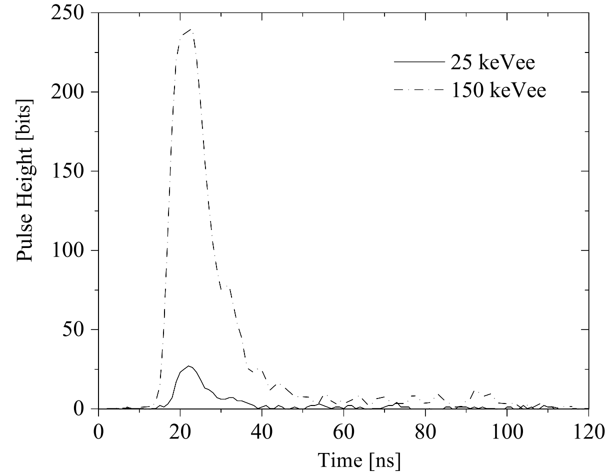

Fig. 2. Two gamma response pulses of differing pulse heights. Each channel represents one nanosecond. The electrical noise, which can be seen easily in between 60 and 120 ns, is on the same scale for both pulses.

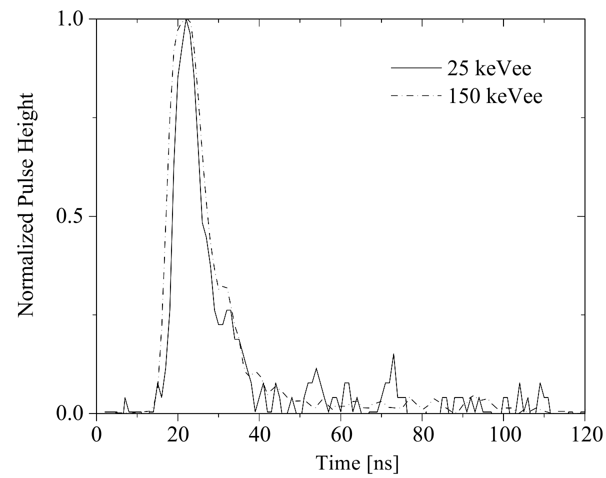

Fig. 3. The same two gamma response pulses of differing heights, normalized to the height of the peak channel. Each channel represents one nanosecond. The electrical noise for the smaller pulse is much larger relative to the pulse size and has a more significant effect on the shape of the pulse.

with the electrons in the scintillation material, and the majority of the signal is prompt fluorescence. Conversely, recoil protons produced by neutron interactions excite triplet states which are longer lived and slow the decay of the response pulse [7]. For this reason, with sufficient timing resolution, a pulse caused by a neutron interaction can be distinguished from a pulse caused by a gamma interaction. This method has been proven to be very successful at neutron energies above 500 keV where the amount of energy deposited in the scintillator is enough to have high signal-to-noise ratios [2]. Fig. 1 shows typical average pulse shapes for gamma and neutron interactions in an EJ-301 liquid scintillator which highlights the longer decay time for neutron pulses and the short decay time for gammas.

At lower energies, the pulse height is similarly lower and the electrical noise in the system begins to have a more significant effect, which can be seen in Figs. 2 and 3. In Fig. 2, two gamma pulses of differing heights are shown, and for each the noise from the electronics is of similar magnitude. When the pulses are normalized to unit height, shown in Fig. 3, the noise becomes much more significant in the shape of the smaller pulses. This increased noise level can cause gamma pulses to look more similar to the neutron pulses due to the noise causing the pulse to appear to have a longer decay time. In this work, the pulse shape classification (PSC) method previously developed at Rensselaer Polytechnic Institute (RPI) [8] is further developed to accurately characterize pulses in the low energy region where that noise is significant.

2. Experimental setup

The detector used for these measurements was a 12.7 cm diameter, 1.27 cm thick EJ-301 liquid scintillation detector coupled to a 12.7 cm diameter Electron Tubes 9823B series photomultiplier tube. The pulses were recorded using an Acqiris AP240 8-bit digitizer with GHz sampling rate (1 ns resolution). The detector thickness was chosen to minimize the gamma background while still providing sufficient neutron detection efficiency. This allowed the bias voltage to be set to 2200 V in order to amplify the low energy pulses.

3. Method

3.1. Energy calibration

In order to determine the lowest measurable energy for the system, a correlation between the pulse integral and the incident gamma ray energy must be determined. Energy calibration was performed with two gamma sources, a 43.8 mCi ^{241}Am source, utilizing the 59.5 keV decay gamma, and a 3.53 μCi ^{137}Cs source, utilizing the 30.97 keV self florescence gamma. The correlation is presented in the equation in Fig. 4. This shows that the lowest detectable energy deposition is approximately 13 keVee.

3.2. Average pulse shape determination

The PSC method used in this work relies on determining average neutron and gamma pulses and doing a comparison to determine if an unknown pulse is more similar to the gamma or the neutron average shape. The determination of these average pulse shapes can be shown in the following sections.