Unfolding of Am-Be Neutron Spectrum Using Machine Learning

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Abstract

This project involves using Machine Learning to differentiate between neutron and gamma responses, especially below 2 MeV energy level in EJ-301 scintillation detector. The neutron and gamma responses were not distinct in lower energy regions during calibration due to inelastic interactions and resolution effects. Therefore, the goal is to build a classification model to separate the responses and then unfold the dataset to compare it with the ISO spectrum. So far, a pulse template for application of t-SNE has been assembled.

1 Objectives

1. Analysis of relevant research papers.
2. Recording experimental data and assembling a template of pulse shape for different ADC Channels.

2 Introduction

Fast neutrons are the most dominant contributors to the background in the field of rare event search experiments. One of the most common neutron sources used in the field are ^{241}Am-^{9}Be, which have a continuous neutron spectrum. EJ-301, for its excellent pulse shape discrimination properties, is been widely used as a scintillation detector. The scintillation response of detector is nearly linear in case of electron recoil events and heavily non-linear in case of nuclear recoil events. So, these two energies need to be calibrated separately and this can be done by using an unfolding method. In order to get that we model the neutron interaction in the scintillator. Next we build a response matrix that connects the scintillator's light output to the energy of the incident neutron. To acquire the incident neutron energy spectrum, the response matrix is employed to unfold the experimental distribution.
A research group in NISER has used ^{241}Am-^{9}Be source and calibrated an EJ-301 Detector to obtain detector response to standard neutron and gamma sources. Due to inelastic interactions of the neutron and resolution effects, in the lower energy region($\sim$ 2 MeV), the unfolded spectrum did not match with the ISO spectrum. The problem arised due to the fact that the neutron and gamma responses were not distinct in lower energy region. The large uncertainty in the number of events resulted in over-prediction, when efficiency correction was applied.[1]
In this project, we are first using tSNE to see if the neutron and gamma responses can be differentiated or not below 2MeV energy level. If yes, we will be trying to build a clustering model which can separate them and then we will unfold the whole dataset again to compare it with the ISO spectrum.

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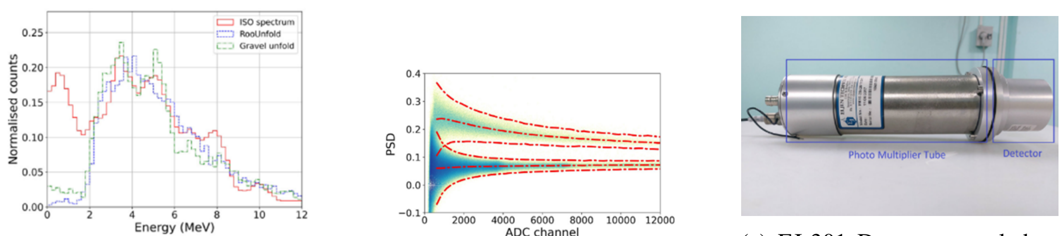
3 Relevant Works

3.1 Energy calibration of EJ-301 scintillation detector using unfolding methods for fast neutron measurement

In order to acquire low radioactive backgrounds, the research uses organic liquid scintillation detectors in underground rare event search experiments. Fast neutrons are one of the main sources of background in such studies. They are formed from rocks through spontaneous fission processes, reactions, and cosmic ray interactions. The procedure for calibrating EJ-301 liquid scintillation detectors to fast neutron energies using unfolding methods is described in the article. It also covers experimentation and simulation of the EJ-301 liquid scintillation detector, starting with the creation of the detector geometry and ending with the addition of optical properties, Birks' effect, and detector resolution effect. In order to get the input Am-Be neutron energy spectrum and calibrate the detector to the neutron energy scale, several unfolding techniques are utilised.



(a) Unfolded Neutron Spectrum

(b) PSD Plot

(c) EJ-301 Detector coupled to PMT

Figure 1

A Photo Multiplier Tube (PMT) with the model number R7724 manufactured by Hamamatsu was linked to an Eljen Technologies liquid scintillation detector as part of the experimental setup. Using the charge integration approach, a CAEN V1730 digitizer processed the anode output of the PMT using Digital Pulse Processing (DPP) for Pulse-Shape Discrimination (PSD). The output of the digitizer was linked to a computer. The PSD parameter, which is defined as the ratio of integrated charge in the short and long gates, was used to determine the appropriate gate values (30 ns and 280 ns for the short gate and long gate, respectively) to differentiate gamma and neutron events. To get the best Figure Of Merit (FOM) value, the anode voltage was maintained at +750V, which is a measure of PSD quality. With an energy threshold of 275 keV, the FOM value achieved was 1.14.

Using the detector response data gathered during an experiment, the unfolding approach reconstructs the energy spectrum radiated by a radioactive source. The detector's reaction to the genuine spectrum from the experiment and the detector's response matrix from simulation are both necessary for this operation. A normalised response function that represents the light output of the scintillator for a certain mono-energetic source appears in each column of the response matrix.

The lack of mono-energetic neutron sources necessitates the creation of the response matrix for neutron detection by simulation. 240 neutron response functions with fixed energy ranges of 0.05 MeV to 12 MeV are used in the simulation. The light output of the detector for incident neutrons with a specific energy distribution, can be written as,

$$N = R * \phi \tag{1}$$

where, N represents the detector response in terms of optical photons collected at photo cathode. ϕ is the incident spectrum of the radioactive source at the detector and R is the response matrix. There are various methods to achieve this, but in this paper, two specific methods - Gravel iterative and RooUnfold - are employed for unfolding.

The "G4OpticalPhysics" physics list in GEANT4 has been used to incorporate the appropriate scintillator properties, which were taken from the EJ-301 datasheet, in order to describe the creation of light photons inside the scintillator. In the investigation, the parameters of the scintillator were added to the GEANT4 simulation, and the optical photon spectrum that resulted was compared to the EJ-301 datasheet. The simulated spectrum was discovered by the authors to be in agreement with the datasheet spectrum.

4 Proposed Baseline Algorithm

CNNs have been widely used for image recognition tasks and we find it suitable to solve our problem because of the following reasons;

1. Effectiveness at identifying patterns and features in images
2. Taking additional features as input
3. Capture the temporal structure of the pulse shape information

The waveform data from our detector is a kind of time-series data, which is having a temporal structure. The convolutional layers and max pooling layers can help to extract features from the data. We will try to train the model to recognize the pattern in the images, such as the shape and size of the pulses. Although in traditional image classification tasks, CNNs have not performed well, in the case of waveform data, due to the temporal nature of our data we find CNN to be a plausible solution to our problem.

5 Experiment

5.1 Apparatus and Software

The following resources are used for data acquisition:

1. EJ-301 Liquid scintillation detector
2. V1370 Waveform Digitizer
3. N1470 Power Supply Bin
4. CAEN DPP-PSD Control Software
5. Am-Be Neutron Source

5.2 Data Acquisition

To create a pulse template, we need the pulse shape. For this, we place the source at a distance of about 6cm from the detector, and use the DPP-PSD Control Software in Oscilloscope mode. This returns the current due to a trigger at a point in time. We manually set the detector to record data for around 1000ns per pulse.

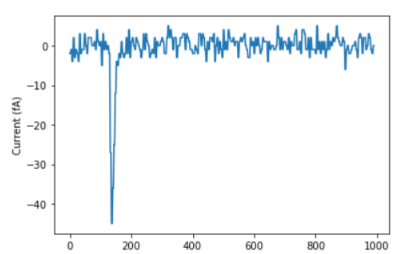
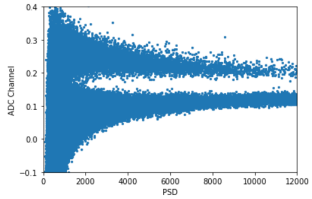


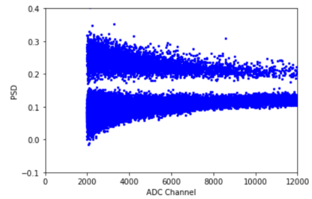
Figure 2: A single pulse detected in oscilloscope mode

5.3 Pulse Template

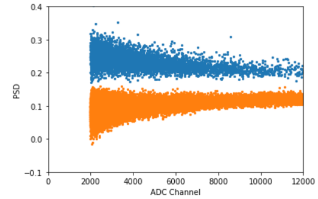
We first integrate the current to find the charge accumulated in the tail of the pulse and calculate PSD parameter for all individual pulses. We plot the PSD to achieve one quite similar to the one



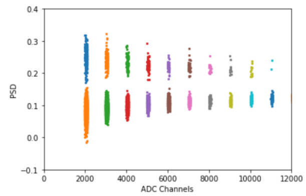
(a) PSD plot



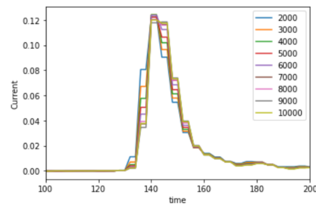
(b) Cut placed at 2000 ADC Channel



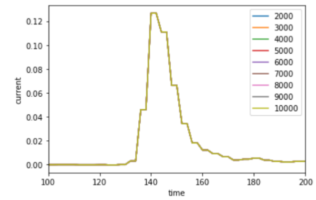
(c) Gamma and neutron PSD plot separated



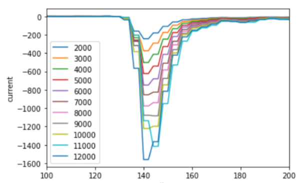
(d) Neutron and gamma pulses isolated for different ADC Channels



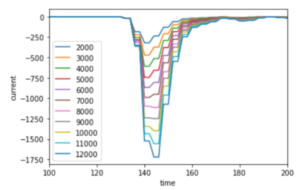
(e) Pulse Template for Neutron Triggers (Normalised)



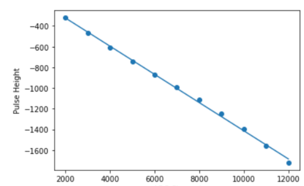
(f) Pulse Template for Gamma Triggers (Normalised)



(g) Pulse Template for Neutron Triggers



(h) Pulse Template for Gamma Triggers



(i) Pulse Height vs ADC Channel

Figure 3: Formation of Pulse Template

achieved by the research group at NISER. We determine an ADC channel from where there is a clear separation between neutron and gamma pulses. Consequently, we place a cut at 2000 ADC channel. Next, we separate the neutron and gamma pulses. We then isolate neutron and gamma pulses at different ADC channels, with a bin size of 100 ADC Channels. We normalize and average the pulses in these bins and are thus able to observe pulse behaviour for different ADC Channels.

From figure 4, the following may be inferred:

1. As can be seen in the pulse template for normalised gamma pulse (4(f)), pulse shape is not energy dependent. Some deviation can be seen in the normalised neutron pulse (4(e)), however that may be attributed to low neutron count recorded. Ideally, the neutron template will look similar to the gamma template. This may be verified by recording data for longer period of time.
2. From figures 4(g) and 4(f), it is evident that pulse height is energy dependent. From figure 4(i), it is clear that this dependence is linear.

The methodology of assembling the pulse templates above may be found in this link.

6 Further Plans

1. Applying a CNN model to achieve a well-separated neutron and gamma response.
2. Unfolding of neutron spectrum and validating it against the ISO spectrum.

References

[1] S. Das, V.K.S. Kashyap, B. Mohanty, Energy calibration of EJ-301 scintillation detector using unfolding methods for fast neutron measurement, *Nuclear Instruments and Methods in Physics Research Section A: Accelerators Spectrometers, Detectors and Associated Equipment, Volume 1042, 2022, 167405*

[2] Aman Upadhyay, Anomaly Detection and Pulse Simulation for Direct Dark Matter Searches, National Institute of Science Education and Research