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Improved pulse shape discrimination in EJ-301 liquid scintillators

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A B S T R A C T

Digital pulse shape discrimination has become readily available to distinguish nuclear recoil and electronic recoil events in scintillation detectors. We evaluate digital implementations of pulse shape discrimination algorithms discussed in the literature, namely the Charge Comparison Method, Pulse-Gradient Analysis, Fourier Series and Standard Event Fitting. In addition, we present a novel algorithm based on a Laplace Transform. Instead of comparing the performance of these algorithms based on a single Figure of Merit, we evaluate them as a function of recoil energy. Specifically, using commercial EJ-301 liquid scintillators, we examined both the resulting acceptance of nuclear recoils at a given rejection level of electronic recoils, as well as the purity of the selected nuclear recoil event samples. We find that both a Standard Event fit and a Laplace Transform can be used to significantly improve the discrimination capabilities over the whole considered energy range of $0-800\ \mathrm{keV}_{ee}$. Furthermore, we show that the Charge Comparison Method performs poorly in accurately identifying nuclear recoils.

1. Introduction

Liquid scintillators such as EJ-301 (which is similar to NE-213 and BC-501) are very popular for neutron detection as they can easily be shaped into the desired size and geometry of a given application and offer fast timing performance. However, since such liquid scintillators are also sensitive to gamma rays, pulse-shape discrimination (PSD) techniques are essential in order to correctly identify neutron interactions in the detector.

The ability to discriminate nuclear recoil (NR) events from electronic recoil (ER) events originates in the particular production mechanisms of scintillation light in organic liquid scintillators. These liquids are aromatic compounds which have planar molecular structures built up from benzenoid rings. Such structures allow for extended groupings of conjugated molecular bonds between unsaturated carbon atoms [1]. This results in some of the valence electrons of the carbon atoms being delocalized in π-molecular orbitals. It is the excitations of these π-electronic states that create the fluorescence observed in organic scintillators. During these excitations, π-electrons can be promoted from the ground state S_0 to excited singlet states S_n or triplet T_n states. For low excitation densities, all excited singlet states above the first excited singlet states S_1 decay rapidly and non-radiatively to the lowest excited singlet state. This state then decays exponentially producing fluorescence in the process.

In contrast, the decay of the triplet state is governed by the diffusion time-scale of the triplet exciton and results in delayed fluorescence in which the intensity does not decay exponentially. NRs exhibit greater energy-loss rates and thus have higher densities of triplet states. Pulses from the ionization tracks of these particles exhibit higher yields of delayed fluorescence, hence decaying more slowly than those of ERs. Scintillation light from EJ-301 has three main decay components: 3.2 ns, 32 ns and 270 ns [2]. The slowest of these decay times is produced by the delayed fluorescence of triplet states.

The different pulse shapes that arise from electronic and nuclear recoils in liquid scintillators can be exploited using different PSD techniques. The most popular techniques applied are the Charge Comparison Method [3] and the Zero Crossing Method [4]. These methods were originally implemented in purpose-designed analogue electronics [5], but with the advent of greater computing power at reduced costs, these techniques have been implemented digitally [6–8]. Digital capture of the full waveform allows for offline processing of events, reducing dead time in data acquisition systems. Techniques designed for analogue circuits do not take advantage of the increased information available in the digital domain. Consequently, new PSD techniques have been developed recently [9–11]. These techniques offer new PSD approaches in the time domain of the waveform, allow frequency-domain and decay-time differences to be investigated using wavelet analysis, and can implement Fourier and Laplace transforms.

Traditionally, the performance of PSD techniques is characterized using the Figure of Merit (FOM), defined as:

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$$\mathrm{FOM} = \frac{\mathrm{PeakSeperation}}{\mathrm{FWHM}_{\gamma} + \mathrm{FWHM}_{n}} \tag{1}$$

where peak separation refers to the distance between the center of the neutron and gamma distributions in a histogram of the discrimination parameter, and FWHM_i is the full-width half maximum of the respective distributions. Hence, the FOM does not provide any information on the energy dependence of the performance of PSD techniques. This precludes a comparison of the various algorithms across different authors that may use different energy thresholds in the calculation of their FOM, and additionally, may mask performance issues of the algorithms in particular at low recoil energy. Therefore, we examined the energy-dependent ability of PSD techniques to discriminate between ER and NR events. Furthermore, we determined the efficiency of EJ-301 for detection of neutrons as a function of energy.

2. Setup

The fast neutron detector used in this work is a 3 in. cell of EJ-301 liquid organic scintillator optically coupled to a fast photomultiplier tube (PMT), type 9821KB manufactured by ET Enterprises. The detector response to neutrons was characterized at the Physikalisch-Technische Bundesanstalt (PTB) in Braunschweig, Germany, using a deuterium ion beam hitting a Ti(^{3}H) target. The deuterium ion beam energy (3.356 MeV) was chosen to produce (2.500 ± 0.010) MeV (k=1 according to [12]) monoenergetic neutrons via ^{3}H(d,n)^{4}He nuclear reaction, in the direction of the ion beam. The detector was placed 3 m from the target. The output of the PMT was connected to a CAEN DT5751 digitizer, which samples at 1 GHz with a resolution of 10 bits. This digitizer has a 1 V dynamic range. A 1 MeV_{ee} pulse from an ER event in the PMT produces a 550 mV signal.

Data were collected at three different nominal beam current settings to study the effect of neutron flux on the performance of the detector. The detector was placed such that the neutron beam was parallel to the normal of the front face, defined as an angle of 0°. The distance between the front face of the detector and the active layer of the target was (3000 ± 2) mm (k=2 [12]) for all measurements. Additional data were taken at each setting with a shadow cone, made of iron and polyethylene, placed between the target and the detector to measure the in-scatter of neutrons, as illustrated in Fig. 1. At the highest nominal beam current, data was also collected with an angle of 90° between the direction of the ion beam and the front face of the detector. In the 90° orientation the detector is rotated such that the neutron flux is incident on the side of the detector, rather than the front face.

These datasets are listed in Table 1 with their known fluxes as measured using calibrated detectors at PTB. Dataset 4 has a greater flux than dataset 1, despite the beam conditions being the same, due to the greater cross-sectional area the detector presents to the neutron beam in this orientation. The known flux in Dataset 4 is slightly higher than can be attributed to geometric factors alone, as the nominal beam charge for Dataset 4 is 5.6% greater than in Dataset 1.

The response of EJ-301 to ERs is known to be linear. Data presented in this work is therefore given in terms of the electron recoil equivalent energy keV_{ee}. This energy scale is set using the Compton backscatter edge of gammas from ^{60}Co, ^{137}Cs and ^{54}Mn, measured from data collected with the detector in the experimental hall. The background rate of ER events in the experimental hall was measured during an overnight measurement.

Table 1
Data for the irradiation of the detector in the neutron field with a mean energy of 2.5 MeV.

Data set	Current	Orientation	Nominal charge [μC]	Flux [s^{-1}]
1	1.5 μA	0°	2721	16,400 ± 700
2	300 nA	0°	1014	3080 ± 140
3	35 nA	0°	56.17	340 ± 15
4	1.5 μA	90°	2883	22,200 ± 970

A total of 80 million waveforms (amounting to 85 GB) were collected from the neutron source, background, and calibration gamma-sources, and stored for offline processing.

3. Discrimination algorithms

As EJ-301 features different decay constants for NR and ER signals, a variety of methods can be used to discriminate the corresponding waveforms. Five PSD algorithms were implemented in a C++ program to perform offline analysis of the data and compute discrimination parameters for each waveform. These algorithms, described in detail below, are the Charge Comparison Method (CCM), Pulse Gradient Analysis (PGA), Fourier Series Expansion (FSE), Laplace Transform (LAP), and a fit to standard events (SEF). Typical scintillation pulses last for 0.5 ns per keV of energy deposited. Each digitized waveform was 525 ns in duration, with the trigger falling between 78 and 94 ns. The first 40 ns were used to calculate a simple baseline average as well as the baseline RMS to indicate the noise level, and the integral of the pulse yields the energy.

3.1. Charge Comparison Method

The Charge Comparison Method (CCM) [6–8,13–17] predates modern digital computing and was first implemented via passive electronics [4]. In this method, the baseline-subtracted waveform is integrated over two time windows of different lengths, called *slow* and *fast* or *long* and *short*, respectively. The start of these integral windows is the onset of the pulse, which is defined here as the point at which the waveform exceeds 3σ of the baseline RMS (as shown in Fig. 2). The lengths of the two windows are generally set to match the decay modes of the detector. As a NR pulse will decay more slowly than an ER pulse, the slow integral value I_{slow} will be larger for NR waveforms than for ER, while the fast integral values I_{fast} are typically comparable for both ER and NR waveforms. We have optimized these times according to the traditional Figure of Merit [18] and found that values of 50 ns for the fast window and 310 ns for the slow window result in optimal discrimination. The discrimination parameter is the ratio of the two integral values,

Fig. 1. The irradiation setup of the EJ-301 detector (left) corresponding to the 0° orientation in Table 1. The shadow cone is visible toward the right. The neutron beam enters the setup from the right.