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Neutron spectroscopy by thermalization light yield measurement in a composite heterogeneous scintillator

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ABSTRACT

An exothermic neutron capture reaction can be used to uniquely identify neutrons in particle detectors. With the use of a capture-gated coincidence technique, the sequence of scatter events that lead to neutron thermalization prior to the neutron capture can also be used to measure neutron energy. We report on the measurement of thermalization light yield via a time-of-flight technique in a polyvinyl toluene-based scintillator EJ-290 within a heterogeneous composite detector that also includes ^{6}Li-doped glass scintillator. The thermalization light output exhibits a strong correlation with neutron energy because of the preference for near-complete energy deposition prior to the ^{6}Li(n,t)^{4}He neutron capture reaction. The nonproportionality of the light yield from nuclear recoils contributes to the observed broadening of the distribution of thermalization light output. The nonproportional dependence of the scintillation light output in the EJ-290 scintillator as a function of proton recoil energy has been characterized in the range of 0.3–14.1 MeV via the Birks parametrization through a combination of time-of-flight measurement and previously conducted measurements with monoenergetic neutron sources.

1. Introduction

Capture-gated neutron detection has shown great promise in neutron spectroscopy [1–4] due to the quasi-full energy deposition prior to neutron capture and the resulting reduced continuum in the detector response function. The capability to perform both thermal neutron detection and fast neutron spectroscopy in a single detector makes the capture-gated detection attractive in various applications. Here, we report on the neutron spectroscopic measurement of a recently developed heterogeneous composite scintillator that includes polyvinyl toluene (PVT)-based scintillator EJ-290 and ^{6}Li-doped scintillating glass (GS20) rods. The composite detector exhibits excellent gamma/neutron discrimination capabilities due to the large Q-value of the neutron capture reaction ^{6}Li(n,t)^{4}He and has shown the advantage of low gamma misclassification rate for neutron detection in abundant gamma background, such as detection of delayed neutron emission from fissionable materials [5]. Fast neutron spectroscopy can benefit such applications because the neutron energy information provides insights about the nature of the neutron source. In this work, the neutron time-of-flight (TOF) was used to determine the neutron energy and, in conjunction with the capture-gated technique, the correlation between the light output of neutron thermalization pulse and the incident neutron energy was investigated. The scintillating polymer EJ-290 [6,7] and its equivalents BC-490 and NE-120 have already been used for constructing capture-gated detector prototypes and find their applications in radiation dosimetry [8] and nuclear safeguards [9]. However, the light yield nonproportionality of EJ-290 scintillator has not been measured. Here we describe the characterization of proton recoil light yield nonproportionality of the EJ-290 scintillator by use of spectroscopic capture-gated measurements in a composite heterogeneous detector based on EJ-290 scintillator and ^{6}Li-doped glass (GS20). Spectroscopic measurements are aided with Monte Carlo simulation of detector response, which allows the EJ-290 nonproportionality to be parametrized using the Birks model.

A detailed description of the detector geometry optimization, prototype fabrication, and performance characterization can be found in Refs. [7,10]. The composite detector exhibits pulse shape discrimination (PSD) properties due to the different scintillation decay times of the two distinct materials used in the composite. The EJ-290 scintillator was selected as the neutron moderation material for two major reasons: first, the light emission and absorption spectra of the EJ-290 scintillator and GS20 glass are compatible and allow light transmis-

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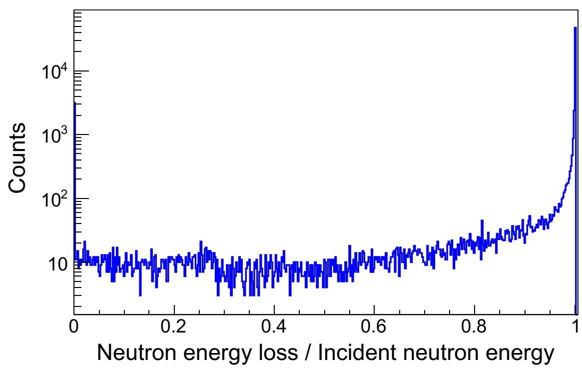

Fig. 1. Simulated ratio of the neutron energy deposition at the time of capture to its incident energy in the EJ-290 scintillator for neutrons incident from a ^{252}Cf fission source. In the Geant4 simulation, the geometry and material composition of the fabricated composite scintillator were used [17]. A point source with ^{252}Cf fission spectrum was directed at the side of the detector. A total of 62,948 captured neutron events are shown.

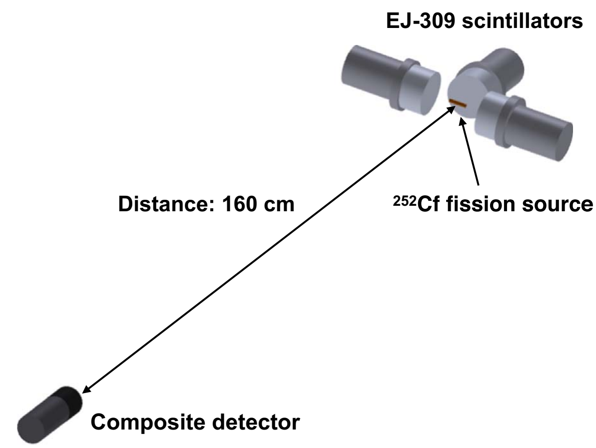

Fig. 2. Experimental setup for the TOF measurement.

sion; second, the EJ-290 casting resin is relatively flexible for fabrication because it can be mixed with other materials in the form of scintillator solvent and cured. When a neutron is captured in the composite detector, two scintillation pulses are usually generated. Prior to the neutron capture reaction ^{6}Li(n,t)^{4}He, the neutron is thermalized in the PVT component of the scintillator, where multiple neutron scatters typically take place in rapid succession. The light output from those multiple scatters is detected using a photomultiplier tube as a single scintillation pulse, referred to as the thermalization pulse. The thermalization pulse precedes the neutron capture pulse, which is used to identify a neutron event. When a thermalization event is correlated to a capture event, the light output of the thermalization pulse is highly representative of the neutron energy on an event-by-event basis. This strong correlation can be understood by considering the dependence of the capture probability on the extent of neutron thermalization. As illustrated in Fig. 1, the results from a Geant4 Monte Carlo simulation show that 75% of the neutrons lose more than 99% of their energy by proton and carbon recoils at the time of capture when the composite detector is irradiated with ^{252}Cf neutron source. Therefore, the thermalization pulse is a strong indicator of the incident neutron energy since the majority of the captured neutrons lose most of their energy to thermalization. It is noteworthy that, although the term "thermalization pulse" is used, not all of the captured neutrons are fully thermalized at the time of capture. A fraction of neutrons are captured at the time their energy is in the epithermal region or above. The ^{6}Li neutron capture cross section resonance centered at 240 keV causes a fraction of neutrons to capture when their energy is in the vicinity of this region [11]. In addition, for a given incident neutron energy, the thermalization light output is broadened due to a variety of thermalization histories and the light yield nonproportionality [12,13]. Nevertheless, the strong correlation of the light output to incident neutron energy in capture-gated detectors is appealing for spectroscopic applications. Various types of ^{6}Li-doped plastic [14] and liquid scintillators [15,16] have been developed recently. This further motivates experimental studies that can improve the understanding of the spectroscopic characteristics of ^{6}Li-doped detectors, which will aid their optimization and use in applications..

2. Experiment

2.1. Experimental setup and data analysis procedure

The relationship between the light output of the EJ-290 scintillator and the incident neutron energy was characterized using TOF and previously conducted monoenergetic neutron measurements [17]. Using neutron TOF measurements to characterize spectral response of non-gated scintillators has been performed in a number of earlier studies [18,19]. In this work, the neutron TOF measurement is used in conjunction with the capture-gated technique, which requires the time correlation of three events: gamma event to tag the fission event timing, neutron thermalization event, and neutron capture event. The TOF measurements were performed by tagging the fission events produced in a ^{252}Cf source with a spontaneous fission rate of 20.9 μCi over a period of 120 h. Prompt neutrons and gamma rays are emitted nearly simultaneously in a fission event, so that the time of fission can be tagged using gamma rays, while the energy of neutrons detected in the composite detector can be determined from the neutron TOF. The experimental setup is depicted in Fig. 2. In the measurement, three calibrated EJ-309 liquid scintillation detectors were placed 5 cm away from the ^{252}Cf source. The composite detector was placed 1.6 m away from the source and 1 m above the concrete laboratory floor. A gamma event identified through PSD in any one of the three EJ-309 detectors was used as the initial signal of a fission event. Events within the TOF acceptance window of $50\,\text{ns} < \text{TOF} < 410\,\text{ns}$ were selected as neutron thermalization pulse candidates from the composite detector, corresponding to incident neutron energies E_n of $5\,\text{MeV} > E_n > 80\,\text{keV}$. The thermalization pulse cannot be distinguished solely on the basis of pulse shape, since both the gamma rays and neutrons interact with the EJ-290 scintillator, which does not exhibit PSD. The thermalization pulse is therefore selected as the pulse preceding the neutron capture pulse within an estimated range of neutron diffusion time. The neutron capture pulses were identified through a two-dimensional criterion based on a fit of a pulse to a combination of standard pulse shape parameter (ratio of the pulse tail area to total pulse area) and the total area, as described in Ref. [7]. Only the events that lie within the 3σ region of the neutron peak area were selected as neutron capture events. Simulations of the composite detector conducted using the Geant4 Monte Carlo code [20] reveal the mean neutron thermalization-to-capture (diffusion) time of 2.67 μs, with $> 99\%$ of the capture events having a diffusion time $< 50\,\mu\text{s}$ [17]. Therefore, an inter-event timing gate of 50 μs, along with the pulse shape consistent with the event taking place in the EJ-290 scintillator, were used to select the thermalization events that precede the neutron capture pulses..

2.2. Resolution and calibration of the data acquisition system

The digitizer used for data discretization (CAEN DT5730) has a sampling interval of 2 ns. The time delay among different digitizer channels was determined and corrected for by placing all detectors at equal distances from a ^{60}Co gamma source and using the two gamma rays that are emitted simultaneously following the ^{60}Co beta decay. The data acquisition system (DAQ), including the photomultiplier rise time,