Nuclear Instruments and Methods in Physics Research A 803 (2015) 47–54

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

Response of the Li-7-enriched Cs_2LiYCl_6:Ce (CLYC-7) scintillator to 6–60 MeV neutrons ☆

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ARTICLE INFO

Article history:
Received 30 June 2015
Received in revised form
24 August 2015
Accepted 31 August 2015
Available online 24 September 2015

Keywords:
CLYC-7
Fast neutrons
Cyclotron
Pulse shape discrimination
Light output

ABSTRACT

We discuss a test campaign designed to irradiate the ^{7}Li-enriched $Cs_2LiYCl_6:Ce^{3+}$ (CLYC-7) scintillator with 6–60 MeV neutrons using the cyclotron located at the Crocker Nuclear Laboratory in Davis, CA. CLYC-7 is a newly developed scintillator that exhibits the ability to make good γ-ray measurements and has the ability to detect and discriminate fast neutrons via pulse shape discrimination (PSD) while functioning as a spectrometer. This allows a single detector to make good measurement of both stimuli simultaneously. The response of this scintillation detector has been investigated below 20 MeV [1] but has yet to be explored for energies greater than 20 MeV. Understanding the spectral and pulse shape response across a broad energy range is important for any radiation detection instrumentation capable of detecting multiple species. At the highest energies sampled, the CLYC-7 PSD demonstrated not only the standard electron/proton separation expected in a mixed γ/n field but the ability to discriminate locally produced deuterons, tritons and α particles. We show the results from the four different neutron beam energies sampled during the experiment. Lastly, we present the results obtained for relating the light output equivalence between electrons and protons/deuterons.

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1. Introduction

$Cs_2LiYCl_6:Ce^{3+}$ (CLYC) is an inorganic crystal scintillation detector that is unique in its ability to make measurements of γ-ray lines with good energy resolution ($\delta E/E \sim 4.5\%$ at 662 keV) and the ability to detect and discriminate incident neutrons – from γ rays – based on differences in the scintillation light decay times (on the order of nanoseconds vs. microseconds).

One of the components of CLYC is Li, which in its natural abundance contains 7.5% ^{6}Li. This isotope has a large neutron capture cross-section ($\sim$1 kilobarn) at thermal neutron energies and is typically employed for thermal neutron detection. An incident neutron captured by the ^{6}Li yields a detectable α particle (and triton) in an exothermic reaction that imparts 4.78 MeV to the two particles. Previous works [2–6] have reported on the development and performance of CLYC for thermal neutron detection. The large thermal neutron cross-section of ^{6}Li makes CLYC ideal for thermal neutron measurements; when CLYC is used for fast neutron detection, as shown by [7–10], the large thermal neutron peak present at a fixed energy in pulse shape space reduces the effectiveness of this modality. To utilize CLYC as a fast neutron detector, depleting the material of ^{6}Li and hence enriching with ^{7}Li, would lead to a scintillator nearly devoid of isotopes with a large thermal neutron capture cross-section. The ^{7}Li-enriched CLYC scintillator (hereafter CLYC-7) can thus be used as a γ-ray/fast neutron detector. CLYC-7 has all the same properties as CLYC but with the ability to serve as a spectrometer for both γ rays and fast neutrons without the thermal neutron component.

Aside from standard nuclear physics or homeland defense applications for which fast neutron/γ-ray detectors are employed, the ideal platform for CLYC-7 would be on a spacecraft, either from Earth orbit at 1 astronomical unit (A.U.) or near the Sun in the inner heliosphere, for studying the fast neutron/γ-ray emission from the Sun. One issue to consider in near-Earth orbit for space-based solar γ-ray/neutron detection is the high-flux, charged-particle environment. To combat these effects, one would use anticoincidence shielding (plastic scintillator) around the detector array and the appropriate triggering electronics set-up to produce a veto signal to reject these events. This method has been previously implemented for space instrumentation and successfully aided detection systems measuring high-energy, neutral emission from the Sun [11]. As in the example instrument given in the previous reference, typically instrumentation for the detection and measurement of these stimuli is designed to make either a good measurement of one species – with the other species detected for *free*, at less than optimal performance – or require disparate

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http://dx.doi.org/10.1016/j.nima.2015.08.080
0168-9002/Published by Elsevier B.V.

instrumentation for both. Making a good measurement of both with a single instrument has not been feasible in the ~MeV regime prior to the development of this scintillator. Additionally, the modestly sized CLYC-7 scintillator, coupled to a compact light readout device (e.g., silicon photomultiplier) and operating with low power, would meet the strict criteria for mass, power, and size imposed on spacecraft instrumentation.

Recent work [1] has been performed to characterize the response of CLYC-7 with monoenergetic neutrons up to 20 MeV. The work presented herein discusses a campaign to determine the response of CLYC-7 to 6 MeV – 60 MeV neutrons.

2. Experimental methodology

The CLYC-7 scintillation detector was irradiated with high-energy neutron beams at the Crocker Nuclear Laboratory (CNL) located on the campus of the University of California – Davis in March of 2015. The CNL facility houses a 76″-isochronous cyclotron, which is capable of accelerating charged particles (protons, deuterons, α particles, and helions) from several 10 s of MeV to greater than 100 MeV. Fast neutrons are produced via a spallation reaction between accelerated protons and a thick beryllium (Be) target: $^{9}Be(p,n)^{9}B$ (Q value = −1.85 MeV). The Be target was encapsulated in a copper (Cu) housing with a front thickness of 0.51 mm, through which the protons traversed before striking the Be target, and a rear thickness of 6.35 mm. The proton beam energies used were: E_p = 20.4 MeV, 30 MeV, 45 MeV, and 67.5 MeV (highest proton energy achievable). The specific energy loss (dE/dx) due to the proton passing through the Be target and the Cu foil, as determined via SRIM simulations [12], and the Q value of the reaction lead to a continuum neutron spectrum with endpoint energies of E_n = 5.9 MeV, 18.7 MeV, 36.1 MeV, and 60.5 MeV. The beam current used at each energy was 200 nA, 50 nA, 200 nA, and 80 nA–100 nA, respectively. A steel collimator (length = 1.6 m) forms an on-axis beam of neutrons that exits from an aluminum window 2.85 m away from the target. The expected beam flux at the exit was on the order of 10^4 n cm^2 s^{-1} at 30 MeV and above; the flux at lower energies is more difficult to ascertain [13]. Data from 12.5 MeV and 14.6 MeV have yielded measured beam fluxes of 30 n cm^2 s^{-1} and 90 n cm^2 s^{-1}, respectively.

The 25.4 mm × 25.4 mm × 25.4 mm CLYC-7 scintillator cube (enriched to 99.93% ^{7}Li) is housed on five sides in 3.175-mm-thick aluminum with a 23 mm × 23 mm × 3.1 mm quartz window on the sixth side (Fig. 1). The scintillator is wrapped with Teflon tape and supported on the top and bottom with 1-mm-thick optical pressure pads. The light-readout device is coupled to the scintillator volume at the quartz window. For this campaign, we used a 51 mm (diameter) Hamamatsu super bialkali photomultiplier tube (PMT) (R6231-100) and associated PMT base (E-11897). The PMT was coupled to the quartz window via optical grease and wrapped with black electrical tape (Fig. 2). Because the surface area of the PMT is larger than the quartz window, a layer of a diffuse white reflector was placed on the exposed area of the PMT prior to wrapping.

The fast output signal from the PMT anode was read directly into one channel of a 16-channel VME-based flash analog-to-digital converter (FADC) manufactured by Struck Innovative Systeme (model no. SIS3316) [14]. The module digitizes the input pulse (5 V range, 50 Ω impedance) and performs pulse height analysis and PSD. The digitizer was set to internally trigger based on a trapezoidal filter; the system was enabled to run in CFD mode such that analysis was always performed at the same part of the pulse, regardless of the amplitude. A second (programmable) trapezoidal filtering method, based on a moving average window, was used to achieve higher quality performance in energy resolution ($\delta E/E$) compared to simply integrating the charge over the entire pulse, i.e., we observed an improvement of ~1–2% in the full width at half maximum (FWHM) between the two methods. The energy filter algorithm allows the user to set a peaking time (P) and gap time (G) that builds two sums over P, separated by G, from the raw ADC input values, resulting in a trapezoid [15]. This is a standard method used in digital signal processing, allowing the user to optimize the trapezoid shape and flat top to obtain the best performance for a given detector. An additional parameter, the decay correction (α), was implemented to ensure that the trapezoid was symmetric and returned to baseline.

PSD is performed by allowing the user to tune programmable gates (accumulators) that can be set to integrate the input pulse over a given region for a given length of time. Offline PSD analysis was performed using the traditional charge integration method [16] given by the following expression:

$$1-\frac{Q_S}{Q_I} \tag{1}$$

where Q_S (Q_I) is the *short* (*intermediate*) integration gate length. The length of the *long* integration gate, Q_L, was set to integrate the total charge. The bias voltage on the detector was provided by one channel of a 32-channel high-current ISEG high voltage supply [17] powered via a Wiener MPOD mixed crate [18].

At CNL, the CLYC-7 detector was placed 2 m from the beam exit to achieve high statistics in a reasonable amount of time given that the efficiency to fast neutrons is on the order of a few tenths of a percent at a few MeV and increases to ~3% at 20 MeV [1,10]. Extrapolating to 60 MeV, one would expect a continued increase in efficiency. To reduce the γ-ray flux from the spallation reaction, lead bricks (total thickness of 10 cm) were placed in front of the beam exit.

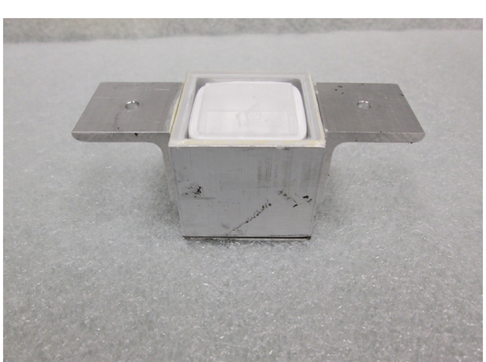

Fig. 1. The 25.4 mm × 25.4 mm × 25.4 mm CLYC-7 scintillation detector packaged in custom-designed aluminum housing.

Fig. 2. The CLYC-7 scintillator (white arrow) shown with 51 mm super bialkali Hamamatsu PMT set-up at the Crocker Nuclear Laboratory experiment room.