Nuclear Instruments and Methods in Physics Research A 821 (2016) 73–80

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

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

A wearable sensor based on CLYC scintillators

Benjamin S. McDonald *, Mitchell J. Myjak, Mital A. Zalavadia, John E. Smart, Jesse A. Willett, Peter C. Landgren [1], Christopher R. Greulich [2]

Pacific Northwest National Laboratory, 902 Battelle Blvd, P.O. Box 999, MSIN: J4-65, Richland, WA 99354, United States

ARTICLE INFO

Article history:
Received 18 November 2015
Received in revised form
9 March 2016
Accepted 10 March 2016
Available online 16 March 2016

Keywords:
CLYC
Wearable
Low power
Unattended sensor
Gamma ray
Neutron
Anomaly detection
Radioisotope identification

ABSTRACT

We have developed a wearable radiation sensor using Cs_2LiYCl_6:Ce (CLYC) for simultaneous gamma-ray and neutron detection. The system includes two $\varnothing 2.5 \times 2.5\ \mathrm{cm}^3$ crystals coupled to small, metal-body photomultiplier tubes. A custom, low-power electronics base digitizes the output signal at three time points and enables both pulse height and pulse shape discrimination of gamma rays and neutrons. The total counts, anomaly detection metrics, and identified isotopes are displayed on a small screen. Users may leave the device in unattended mode to collect long-dwell energy spectra. The system stores up to 18 h of one-second data, including energy spectra, and may transfer the data to a remote computer via a wired or wireless connection. The prototype is $18 \times 13 \times 7.5\ \mathrm{cm}^3$, weighs 1.3 kg, not including the protective pouch, and runs on six AA alkaline batteries for 29 h with the wireless link active, or 41 h with the wireless link disabled. In this paper, we summarize the system design and present characterization results from the detector modules. The energy resolution is about 6.5% full width at half maximum at 662 keV due to the small photomultiplier tube selected, and the linearity and pulse shape discrimination performance are very good.

1. Introduction

Many personal radiation detectors lack the sensitivity and specificity to characterize threats or are operationally burdensome (e.g., heavy or large). Other drawbacks include relatively short (8-h) operating lifetimes and high false alarm rates. At Pacific Northwest National Laboratory (PNNL), we have developed technology to alleviate these problems. These solutions combine new detector materials with low-power electronics and real-time analysis algorithms for teasing threat signatures from noisy data. One promising material is Cs_2LiYCl_6:Ce (CLYC). This elpasolite scintillator combines medium gamma-ray energy resolution (3.9% full width at half maximum (FWHM) at 662 keV) with the ability to detect thermal neutrons via ^{6}Li $(n,\alpha)^3$H neutron capture [1]. Neutron capture events produce a peak in the energy spectrum around 3.2 MeV electron equivalent (MeVee), which is 67% of the 4.8 MeV released from the neutron capture reaction. The primary emissions, due to self-trapped excitation and Ce^{3+} luminescence, have a characteristic decay component of 4.3 ± 0.1 µs, with additional components around 400 ns, and wavelengths ranging from 350 to 450 nm. Gamma interactions also produce core-to-valence luminescence with a fast decay time of 2 ± 1 ns and wavelengths ranging from 250 to 350 nm [2,3]. This effect allows the use of pulse shape discrimination (PSD); however, the PSD performance degrades at higher temperatures [4,5]. Recent work has also demonstrated fast neutron detection and spectroscopy via the ^{35}Cl $(n,p)^{35}$S reaction [6]. The efficiency for fast neutrons is quite low compared with thermal neutrons, and we only focused on discriminating thermal neutrons in this project.

A handful of portable, combined neutron-gamma systems have been created recently. One system, circa 2004, was based on Li:I (Eu), which has roughly 8% FWHM at 662 keV and good thermal neutron efficiency, but no PSD capability [7]. More recently, two systems based on CLYC have been developed by Los Alamos National Laboratory (LANL) and collaborators. The first is a handheld, power-over-Ethernet device called the Compact Advanced Readout Electronics for Elpasolites (CAREE) [8]. This system utilizes a PSD-capable ASIC, consumes 2.28 W on average, achieves count rates up to 20 kHz, and supports various detector sizes. The second, the Advanced Radiation Monitoring Device (ARMD), is battery powered, utilizes the same ASIC, draws approximately 3.6 W, has a similar count rate capability as CAREE, and incorporates four CLYC detectors for greater sensitivity and directionality capability [9]. At least two commercial devices now incorporate CLYC. One is the RIIDEye™ X series made by Thermo Scientific (http://www.thermoscientific.com). It uses a $\varnothing 1.8 \times 3.4\ \mathrm{cm}^3$ crystal in the handle of a handheld device for neutron detection only

* Corresponding author.
E-mail address: benjamin.mcdonald@pnnl.gov (B.S. McDonald).
[1] Now at: Princeton University, Princeton, NJ, United States.
[2] Now at: University of Florida, Gainesville, FL, United States.

http://dx.doi.org/10.1016/j.nima.2016.03.034
0168-9002/

and a larger NaI:Tl or LaBr3:Ce crystal for gamma detection. Another recent commercial device is the F500 made by Target Systemelektronik (http://target-sg.com), which optionally includes a single ⌀5.1 × 5.1 cm^3 CLYC detector for combined neutron and gamma detection.

The use of the same material for detecting gamma rays and neutrons has obvious benefits for reducing the size and weight of personal radiation detectors. However, low-power electronics and computationally efficient analysis algorithms are also key to maximizing battery life. PNNL has developed a number of autonomous radiation detection systems, known as unattended sensors, that feature advances in both areas. A first-generation unattended sensor, completed in 2009, contained two standard NaI:Tl 5 × 10 × 40.6 cm^3 detectors for gamma-ray spectroscopy and eight ^{3}He proportional counters for thermal neutron detection [10]. Each gamma detector had a count rate capability of 10 kcps. Notable features of this system included the low-power electronics for detector readout and bias, which were limited in count rate but consumed an order of magnitude lower power than commercial systems. The unattended sensor also implemented a computationally efficient algorithm developed in earlier efforts to classify energy spectra as either benign or anomalous. This energy windowing technique, known as N-SCRAD, allows for anomaly detection at much lower count rates than possible with traditional isotope identification methods [11].

A next-generation unattended sensor, completed in 2012, integrated the gamma-ray and neutron detection capabilities into one volume using CLYC [12,13]. The unattended sensor contained sixteen ⌀2.5 × 2.5 cm^3 CLYC detectors, each read out by a high quantum efficiency Hamamatsu R9420-100 super bi-alkali photomultiplier tube (PMT) and custom low-power electronics. Although the total active volume was much lower than the original system, the neutron detection efficiency was comparable to much larger first-generation unattended sensor, which used ^{3}He proportional tubes. The next-generation unattended sensor also featured a new algorithm, known as quick ID (QID), for performing isotope identification on computationally limited hardware. The combination of N-SCRAD and QID permits positive identification of known sources and anomaly detection of unknown, weak, or shielded sources. The total count rate limitation of the system was around 3000 cps, which was a tradeoff in low-power electronics design that enabled month-long operation on battery power.

2. Design

2.1. Overview

We have developed a wearable radiation sensor for detecting and identifying illicit radioactive material, dubbed the Low Profile Sensor (LPS). The LPS may be worn on the chest for real-time alarm notification, or used as an unattended sensor. An overall goal of this project was to assess how CLYC performs as a material in a wearable, low-power device. Potential applications of the system include impromptu portal monitoring and long-dwell source characterization. Furthermore, this system is designed for both specialist and non-specialist use. The specialist can monitor anomaly metrics and isotope identification results. The non-specialist can perform surveys, wirelessly transmit data, and wait for feedback from experts. In brief, the LPS offers the following capabilities:

- Combined gamma-ray and neutron detection.
- Greater neutron sensitivity than ^{3}He proportional counters by volume.
- Standard gross count and sigma-over-background alarms.
- Anomaly detection algorithm (N-SCRAD) for enhanced sensitivity to illicit materials and reduced false alarms from naturally occurring radioactive material (NORM).
- Isotope identification algorithm (QID) with 20 template materials.
- Visual and audible alarms.
- Backlit liquid crystal display (LCD).
- USB and Wi-Fi connections.
- Data transfer in ANSI N42.42 format or plain text.

2.2. Detectors

The sensor contains two ⌀2.5 × 2.5 cm^3 CLYC crystals manufactured by Radiation Monitoring Devices, Inc. These detectors were the largest size available during the design phase; ⌀7.6 × 7.6 cm^3 crystals are now offered. We chose two crystals to increase the detection efficiency and provide backup functionality in case one of the components fails. As delivered, the crystals are wrapped with Teflon tape and packaged inside a sealed aluminum housing with a fused silica quartz window, as CLYC is hygroscopic. Event-by-event data from the detectors are summed if they occur within a small time window, thereby moving downscattered events to the photopeak. The crystals are placed relatively close together to maximize this effect, which was studied with MCNP5 V1.60 [14].

2.3. Mechanical design

Fig. 1 illustrates a cross-section rendering of the LPS without its protective pouch. The housing consists of several compartments: an inner housing for the detector and PMT, and separate chambers for the batteries and processing electronics. The detector, batteries, and circuit boards are placed inside a plastic enclosure with overall dimensions of 13 × 7.5 × 18 cm^3. The total mass of these components is 1.3 kg. The enclosure fits inside a padded pouch that can be attached to the body via Modular Lightweight Load-carrying Equipment (MOLLE) straps or placed inside a bag.

Each CLYC detector is coupled to a Hamamatsu ultra bi-alkali R11265-200 PMT via a 1.5 mm thick Eljen Technology EJ-560 optical interface pad. A small amount of Saint Gobain Crystals BC-630 silicon grease is used on both sides of the pad. These pads provide excellent optical coupling that will not leak out over time like optical grease alone. They also offer some protection for the PMT/detector interface against mechanical shocks. The PMT is a square, metallic body, "ultra bi-alkali" type with overall dimensions of 2.6 × 2.6 × 2.2 cm^3. The metal body provides much greater mechanical robustness and magnetic shielding compared with typical glass PMTs. No reflective material was wrapped around the edges of the PMT–crystal interface as the enclosure tolerances were tight and tests indicated that Teflon wrapping did

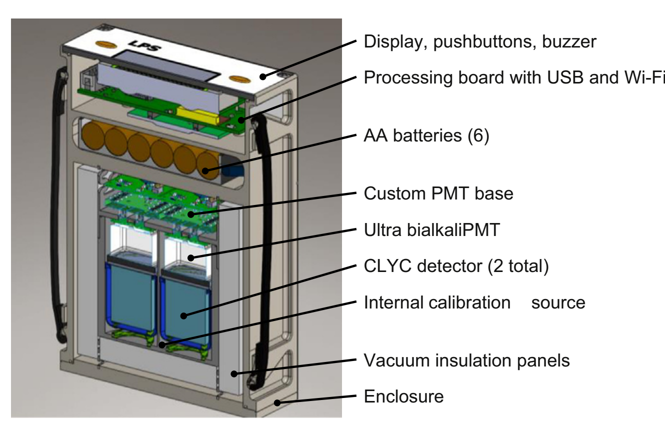

Fig. 1. A cross-sectional view through a SolidWorks^{TM} model of the LPS.