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Gamma–neutron imaging system utilizing pulse shape discrimination with CLYC☆

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ABSTRACT

Recently, RMD has investigated the use of CLYC (Cs_2LiYCl_6:Ce), a new and emerging scintillation material, in a gamma–neutron coded aperture imaging system based on RMD's commercial RadCam™ instrument. CLYC offers efficient thermal neutron detection, fast neutron detection capabilities, excellent pulse shape discrimination (PSD), and gamma-ray energy resolution as good as 4% at 662 keV. PSD improves the isolation of higher energy gammas from thermal neutron interactions (> 3 MeV electron equivalent peak), compared to conventional pulse height techniques. The scintillation emission time in CLYC provides the basis for PSD; where neutron interactions result in a slower emission rise and decay components while gamma interactions result in a faster emission components. By creating a population plot based on the ratio of the decay tail compared to the total integral amplitude (PSD ratio), discrimination of gammas, thermal neutrons, and fast neutrons is possible.

Previously, we characterized the CLYC-based RadCam system for imaging gammas and neutrons using a layered W-Cd coded aperture mask and employing only pulse height discrimination. In this paper, we present the latest results which investigate gamma-neutron imaging capabilities using PSD. An FPGA system is used to acquire the CLYC–PSPMT last dynode signals, determine a PSD ratio for each event, and compare it to a calibrated PSD cutoff. Each event is assigned either a gamma (low) or neutron (high) flag signal which is then correlated with the imaging information for each event.

1. Introduction

To determine the presence of special nuclear materials (SNM), one has to detect and identify characteristic signatures. Neutrons and gamma rays are two signatures of these materials, which when detected can confirm the presence of a particular isotope. Gamma ray detection and imaging techniques are useful for locating SNM; however, dense surrounding materials such as lead can significantly attenuate their intensity and obscure gamma images due to scattering. Neutrons, on the other hand, can easily penetrate dense and high atomic number materials and their detection provides an additional signature for SNM. Low-Z materials (e.g., polyethylene) are effective at moderating neutrons. However, fast neutrons have a low interaction cross-section for these materials and potentially contain added imaging information due to the reduced scattering. Imaging neutrons (thermal and potentially fast), along with gammas, can provide additional verification of the nuclear material's location. Several techniques exist for imaging gammas and neutrons such as telescopic configurations [1], Compton imaging [2,3], and coded-aperture cameras [4,5]. The main challenge with imaging neutrons using scintillation materials is discriminating background gammas which can reduce the overall neutron contrast.

Capabilities for imaging both gammas and thermal neutrons by employing a single scintillation material, CLYC (Cs_2LiYCl_6:Ce), were previously demonstrated with RMD's CLYC RadCam-1 system [6,7]. Discrimination of gammas and thermal neutrons is possible with CLYC since thermal neutron capture reactions (based on ^{6}Li(n,α)t reactions) result in a ~3.5 MeVee peak in the energy spectrum. Using the RadCam software, an energy gate could be applied to the ~3.5 MeVee peak which effectively isolated thermal neutrons in the nuclear image.

One challenge with imaging thermal neutrons using pulse height discrimination (PHD) is that higher energy gammas represent background counts that can be included with the gated

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neutron events. The next generation system, CLYC RadCam-2, addresses this limitation by exploiting the pulse shape discrimination (PSD) capabilities of CLYC.

The secondary products produced from ^{6}Li(n,α)t reactions generate scintillation light in CLYC that inherently have a slower rise and decay times when compared to excitations from gamma-ray events [8]. The differences in time profiles for both gammas and neutrons are quantified by comparing the integrated amplitude of the decay tail to the total integrated waveform. This value, referred to as the PSD ratio by RMD, can be compared to a calibrated PSD ratio cutoff to determine whether the detected event was a gamma or neutron regardless of the energy deposited. Furthermore, the fast neutron cross-section for CLYC (based on ^{35}Cl(n,p) reactions) becomes prominent for incident neutron energies >1 MeV. The secondary proton produces scintillation light with a different time profile compared to gamma-ray events along with an energy deposition that is directly related to the *Q*-value of the reaction (0.615 MeV) and kinetic energy of the incident neutron [9–11]. Once all neutrons are isolated using PSD, an extra energy gate can be applied to image the fast neutrons by excluding the thermal neutrons found around the 3.5 MeVee peak.

This work compares the images of two different neutron sources, 252-Cf and 241-Am/Be, and the effect of PSD on the images.

2. CLYC RadCam-2 system

The CLYC RadCam-2 system incorporates several significant upgrades from the previous generation including PSD capabilities. A picture of the second generation CLYC RadCam system is shown in Fig. 1. This system is lighter and more compact compared to the first generation system since the gamma–neutron shielding is confined to the CLYC–PSPMT pair and the ancillary power/readout components are fully contained in the aluminum housing. The system rests on a tripod with a pan and tilt mechanism that allows for imaging 360° around the camera. The video camera can also be tilted directly up or at any angle down below the horizon. Rotation of the mask by 90° for double coded aperture imaging is autonomous and performed by a stepper motor. Double coded aperture imaging refers to sequential imaging with the mask pattern followed by the anti-mask pattern (rotated 90°). This process enhances the nuclear image quality by reducing background events that do not correlate with gamma or neutron sources in the nuclear camera's field of view.

For the PSD additions, a printed circuit board which contains an amplifier (LTC6400-26) and ADC (AD9230) digitizes the analog waveforms from the last dynode CLYC–PSPMT output (Hamamatsu R2486). The digitized waveforms are then routed to a single-channel, FPGA (Xilinx Virtex 4 evaluation board). A photo of the hardware and mounting setup inside of the RadCam aluminum housing is shown in Fig. 2. The electrical connections between the CLYC RadCam-2 system and FPGA system include: USB, analog γ/n flagged signal input to Keithley acquisition system, CLYC–PSPMT last dynode connection to the FPGA system, and power supplied to the amplifier, ADC, and FPGA (Fig. 3).

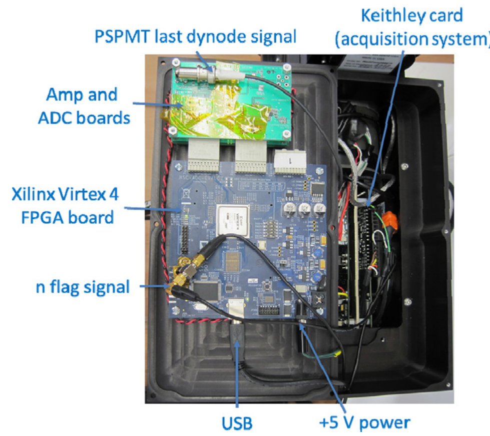

Fig. 2. The neutron-flagged signal generated by the FPGA system is routed to a BNC output on the backside of the RadCam and into an analog input channel of the Keithley acquisition system.

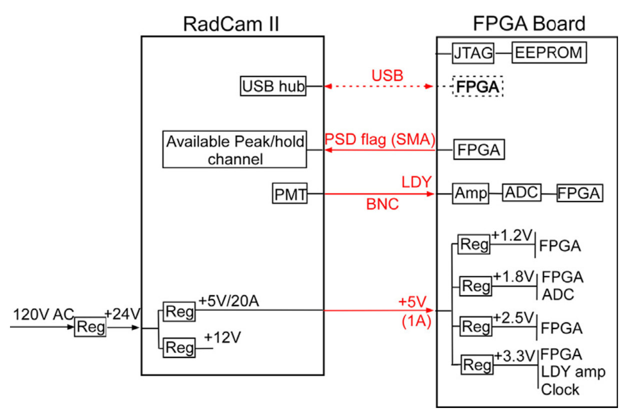

Fig. 3. Power and communication for the FPGA readout system is provided by the CLYC RadCam-2 system. Future implementations of the FPGA system may include PSD binary programming via JTAG and EEPROM upon power up on the full system.

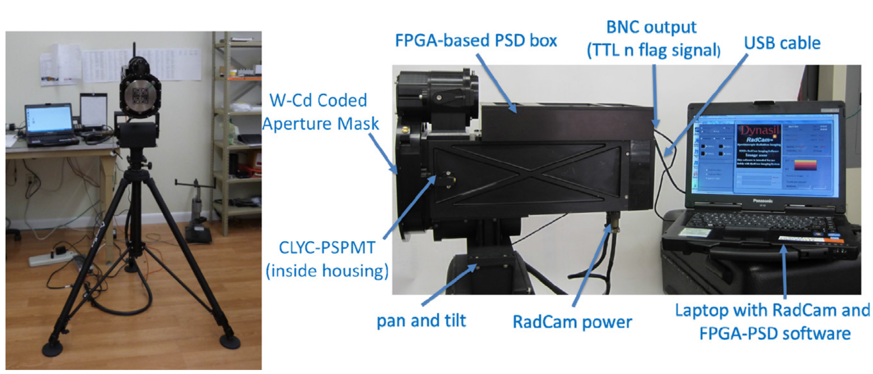

Fig. 1. The CLYC RadCam-2 system components, including: the video camera, Keithley acquisition system, pan and tilt control, and FPGA–PSD system communicate with a laptop via USB. A TTL output has been added for neutron-flagged events, which allows for neutron counting. For size reference, the laptop monitor on the right side of the right figure is 13″ wide.