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Novel imaging technique for thermal neutrons using a fast optical camera

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ABSTRACT

A novel imaging technique for thermal neutrons using a fast optical camera is presented. Thermal neutrons are reacted with ^{6}Lithium to produce a pair of 2.73 MeV tritium and 2.05 MeV alpha particles, which in turn interact in a thin layer of LYSO crystal scintillator to produce a localized flash of light. These photons are directed by a pair of lenses to a micro-channel plate intensifier, and its output is connected to the optical camera, TPX3CAM. The results from the camera are reconstructed through a custom algorithm. Various cutting parameters were found through data analysis to eliminate the background, and they were shown effective in matching the simulated rate of the neutron source. The system is fast with 40 ns decay time and allows free-space light collection, both vastly enhances flexibility of neutron detection.

1. Introduction

Thermal neutron detection has been well studied over the years, developing real-time detection with enhanced sensitivity and spatial as well as temporal resolutions. The sectors that have an interest in a fast neutron camera are reactor instrumentation, material science, cosmic ray detection, and neutron imaging amongst other applications.

A recent report on a fast α-imaging camera [1] has shown that by using a fast single photon sensitive camera, TPX3CAM [2], one can collect photons produced by alpha particles in a thin layer of LYSO scintillator (≈40 ns decay time [3]). Another study on neutron imaging used the same camera but coupled with the ^{6}LiF:ZnS scintillator (order of microseconds decay time) had shown that the thermal neutrons detected this way can produce higher spatial-resolution images compared to traditional neutron imaging [4]. The TPX3CAM has time resolution of 1.56 ns and pixel pitch of 55 μ m, the pixels are arranged in a 256 × 256 matrix. It allows simultaneous measurement of the Time-of-Arrival (ToA) and Time-over-Threshold (ToT) of each pixel. These characteristics provide multitude of variables for signal to noise discrimination.

This optical approach in neutron detection, i.e. scintillator combined with optical lens system, provides a flexible setup for light collection at a wide range of different Field-of-Views (FoV), this enables the detection or measurements to be conducted remotely using radiation-hard optical fibres. This detection technique also magnifies the field of view of a relatively small semiconductor detector by using appropriate lenses for focusing the light produced. The technique presented here is faster in contrast to other optical neutron detection methods over an order of magnitude, nanoseconds compared to microseconds.

The thermal neutrons are converted into a tritium and an alpha by the reaction ^{6}Li(n, α), as formulated,

$$ {}^{6}_{3}\mathrm{Li} + {}^{1}_{0}\mathrm{n} \longrightarrow {}^{3}_{1}\mathrm{H} + {}^{4}_{2}\alpha \tag{1a} $$

With the product energy of:

$$ E_H = 2.73\ \mathrm{MeV\ and}\ E_\alpha = 2.05\ \mathrm{MeV}. \tag{1b} $$

2. Experimental setup

The light-tight TPX3CAM setup is illustrated in Fig. 1. The fast neutrons from the Americium–Beryllium (AmBe) source are modulated by 10 cm of high-density-polyethene (HDPE).

The scintillator is an LYSO crystal measured at 10 × 10 × 0.5 mm^3 with approximately 1 um thick $^{6}Li_2CO_3$ paste on its surface. Utilizing available optics at hand, two 50 mm f/2 lenses were mounted face-to-face (infinity corrected lens setup), providing high light collection

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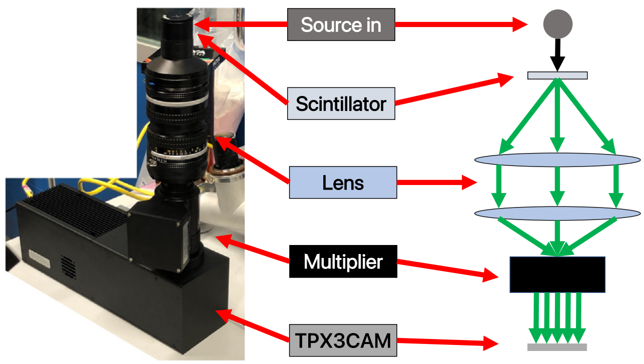


Fig. 1. Left, Photo of the setup. Right, Illustrated setup. A neutron reacts with the ^{6}Li layer of the scintillator, the tritium or the alpha particle produces a flash of light in the LYSO. The light is multiplied by the intensifier, then arrives at the TPX3CAM optical camera. The black arrow indicates the neutron flow and the green arrows indicate the photons flow.

efficiency with a 1:1 magnification. The image intensifier is a micro-channel plate device by Photonis (Cricket). The TPX3CAM is a SPIDR based Timepix3 coupled with a planar silicon sensor, made by Amsterdam Scientific Instruments [5]. The goal of the setup was to have a compact system which can be used for remote monitoring (camera outside of the direct beam) while retaining high spatial resolution.

3. Results and analysis

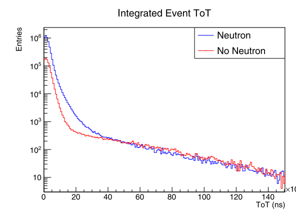
The identification of the neutron signal (or rather the product of the ^{6}Li(n, α) reaction) can be done by clustering a specific number of photons that would arrive at the camera within the decay time of the LYSO crystal.

The LYSO crystal has a photon yield of 27,600 photons/MeV, for 2.73 MeV and 2.05 MeV it produces approximately 75,300 and 56,600 photons respectively. When the particle releases energy into the crystal, quenching effects could suppress the photon yield by a factor of 11 [6]. As photons pass through the crystal and air interface, their direction changes according to Snell's law. The distance between LYSO and the intensifier input is 100 mm, the solid angle reduces the number of available photons. With 410 nm wavelength photons, the intensifier has a quantum efficiency of 27.1% and a sensitivity of 87.5 mA/W . Taking into account the total light collection efficiency, $\approx$ 5–7 photon groups were seen by the camera per thermal neutron. This expected number of photon hits can be lowered by the effects such as reflection on the lens wall, optical attenuation, and hits blending.

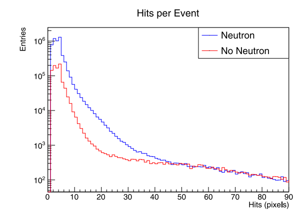
Background includes gamma rays from the AmBe, beta emission from ^{176}Lu in the LYSO, and DAC counts in the intensifier. The rate of the background is shown in Table 1(a).

The challenge of the analysis was to eliminate the background, without risking over-training the signal selection process. The goal was to present a set of cutting parameters which can improve the signal-to-noise ratio. As shown in Fig. 2, various parameters were investigated, the most successful ones were: Integrated ToT, $8 \times 10^3 < x < 40 \times 10^3$ (ns). Number of hits in an event, $15 < x < 50$. Number of clusters in an event, $2 < x < 8$. This was supported by prior calculation that each thermal neutron can be converted to approximately 5–7 photon groups, and these coincides to a circle of r $\approxeq$ 155 um on the camera sensor.

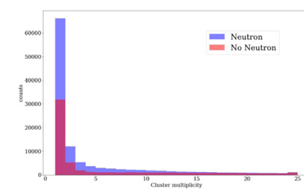
GEANT4 simulation gives a neutron rate of $\approx$1 Hz at the TPX3CAM. The experimental results of the event frequency with a range of source activity (by changing the distance between the source and the scintillator) before and after the cuts were applied are shown in Tables 1. In the after-dataset, by taking away the background, the ratio between the datasets approximates their expected value. The thermal neutron rate also agrees with the simulated 1 Hz.



(a) Integrated ToT



(b) Hits per event



(c) Clusters per event

Fig. 2. Plots showing (top left) the integrated event Time over Threshold (ToT), (top right) number of hits per event, and (bottom centre) number of clusters per event.

Table 1
The event frequency/rate before and after cuts were applied to each dataset, all rates are in Hz.

Source	Reconstructed events	Minus background	Ratio to max-rate
Background	34.2 ± 0.38	0 ± 0.38	-
Max-rate	67.5 ± 0.42	33.3 ± 0.42	1
Half-rate	52.5 ± 0.41	18.3 ± 0.41	0.55
Quarter-rate	40.8 ± 0.42	6.6 ± 0.42	0.2

(a) Before cuts applied.

Source	Reconstructed events	Minus background	Ratio to max-rate
Background	0.8 ± 0.01	0	-
Max-rate	2 ± 0.01	1.2 ± 0.01	1
Half-rate	1.5 ± 0.01	0.7 ± 0.01	0.58
Quarter-rate	1.1 ± 0.01	0.3 ± 0.01	0.25

(b) After cuts applied.

4. Conclusion

While using a weak neutron source ($\approx$1 Hz), thermal neutrons were successfully detected using a neutron converter on a scintillator and a portable single photon detector based on TPX3CAM. The chosen cutting parameters were effective in suppressing the background due to both the LYSO and the source. The obtained results are therefore a good basis and benchmark for further work and can be applied to basic neutron measurements.

Future optimizations of the setup to maximize upfront the neutron/background discrimination will consider removing the lens housing to reduce internal reflections, improve lithium deposition technique for even detection, and investigate neutron-gamma discrimination in ^{6}Li:LYSO scintillator.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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