Novel Imaging Technique for Thermal Neutrons Using a Fast Optical Camera

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Introduction

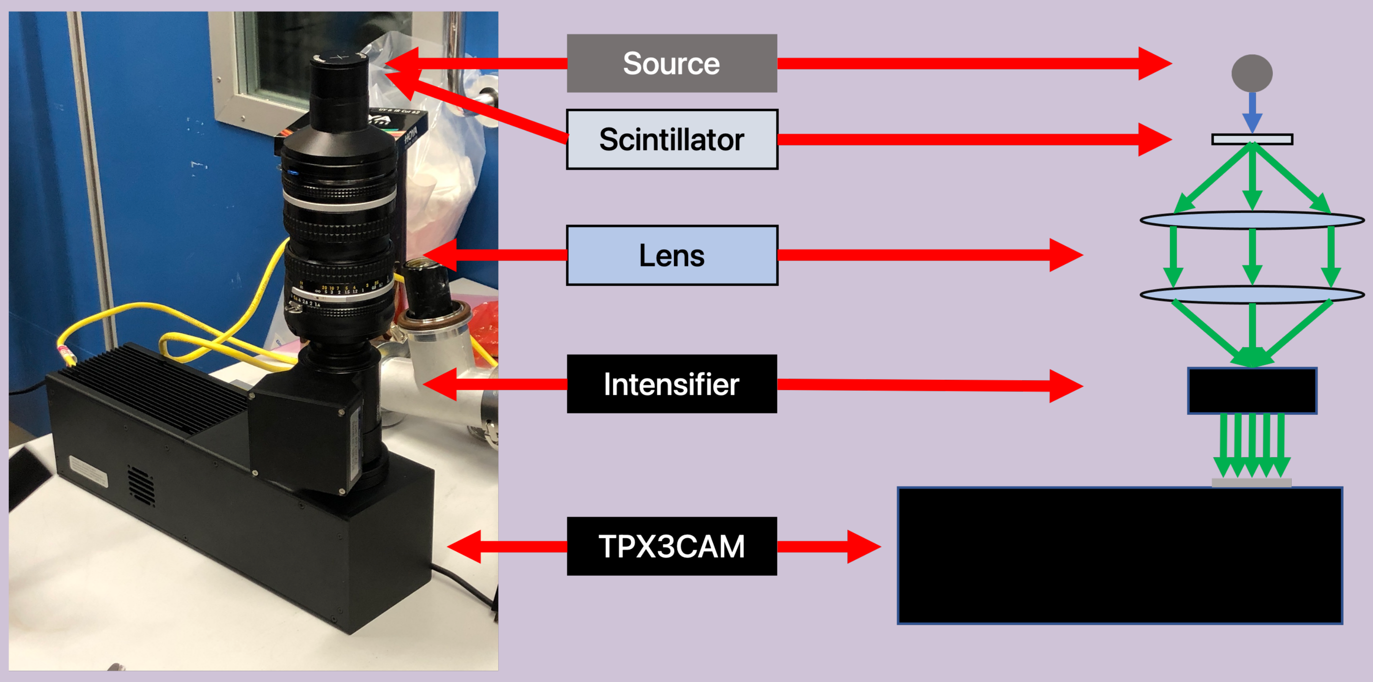
The goal of this project was to detect thermal neutrons using a spatial and temporal sensitive fast and portable optical camera based on Timepix3 and ^{6}Li neutron converter. Previous work with the camera showed that 5.5 MeV alpha could be successfully imaged using LYSO crystal as detecting scintillator[1][2], and neutron imaging [3]. The Timepix3 camera allows real-time imaging of single photons with spatial resolution of ~ 16 um and a temporal resolution of 1.56 ns.

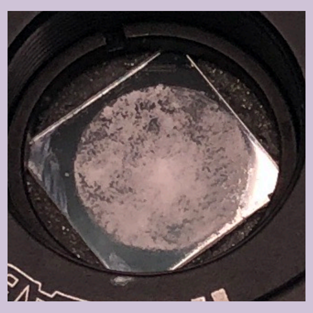
The advantage of the proposed detection method is:

1. The converter and scintillator combination can be made to cover a large area, and the generated photons can be focused via multiple lenses or tapered fibers onto a single camera.
2. The light beam can be directed through optical-fibre or mirrors, which allows remote detection.

The sectors that have an interest in a neutron camera are reactor instrumentation, material science, cosmic ray detection, and nuclear security amongst other applications. For nuclear security, one potential application is fissile material detection using cosmic muons. Neutrons generated by cosmic muons striking the nucleus of the dense fissile material [4] can be detected by this system and it could also complement the Muon Tomography method to improve accuracy [5].

Experiment setup



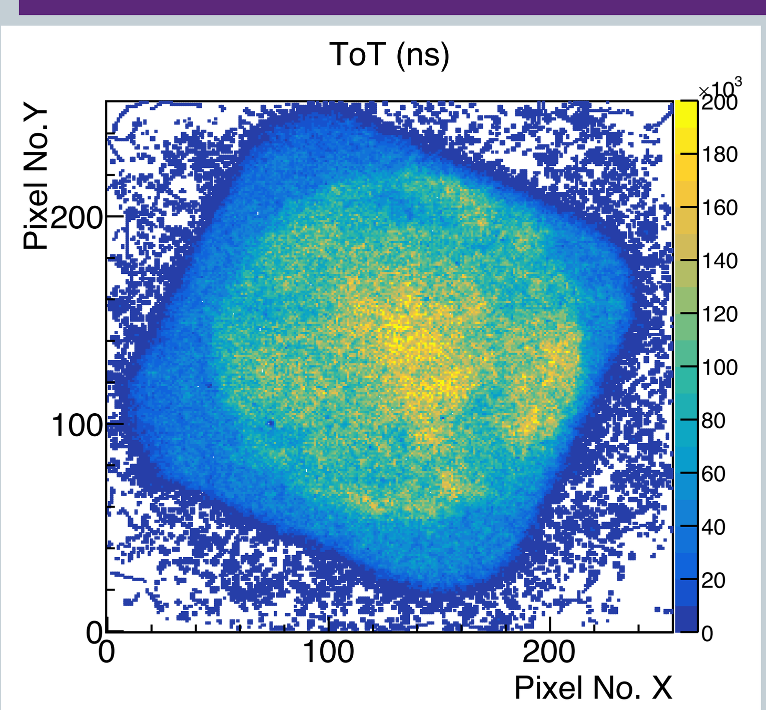


Lithium-6 converts thermal neutrons into Alpha (2.05 MeV) + Tritium (2.73 MeV) → The LYSO crystal scintillates photons proportional to the alpha or tritium energy → The photons are focused onto the input window of the Intensifier (0.5% efficiency) → The intensifier multiplies each photon into a group of photons (20% efficiency)

An Americium-Beryllium (AmBe) neutron source is encased in lead cylinder to reduce the intensity of the 60 keV gamma ray. The source and scintillator are separated by a 10 cm thick high-density-polyethylene moderator.
The neutron detector is composed of a 0.5 mm thick LYSO scintillating crystal with approximately 1 um thick $^6Li_2CO_3$ deposited on its surface. Optical lenses are manually focused so that each detected neutron produces clusters with a minimum number of pixels. The image intensifier is a vacuum microchannel plate device by Photonis (Cricket). The TPX3CAM is a SPIDR based Timepix3 coupled with a silicon planar sensor, made by Amsterdam Scientific Instruments.

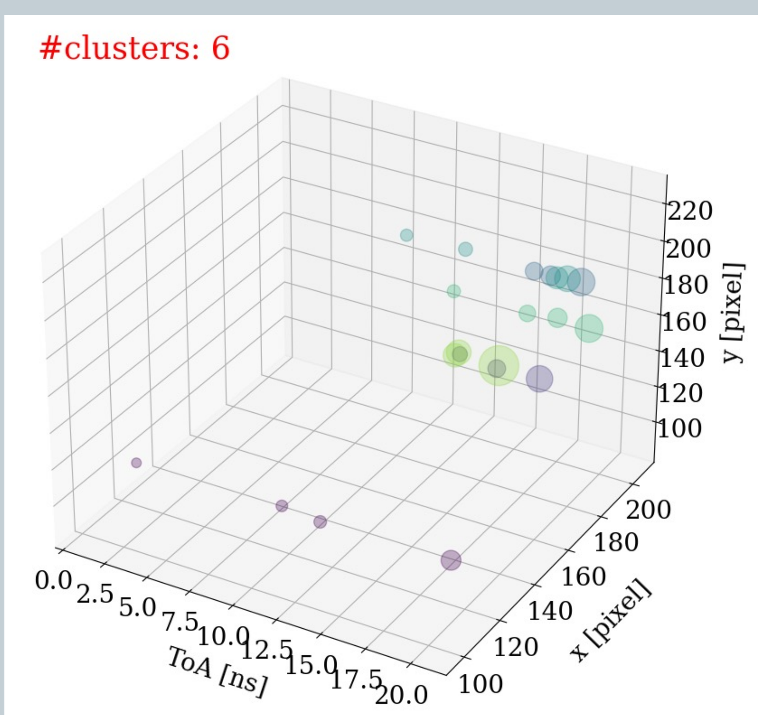
The experiment was repeated with reduced rates by moving the neutron source further away until the cylindrical neutron dosimeter reads a half and a quarter neutron dose. GEANT4 simulation shows that the detection efficiency is 1%, with the thermal neutron rate approximately < 1 Hz.

Data Reconstruction



The top plot shows the difference in number of events in different regions of interest:

1. Inside of the circular Li6 layer.
2. The square LYSO crystal.
3. Outside of the crystal where its mostly DAC noise from the intensifier and cosmic-rays.

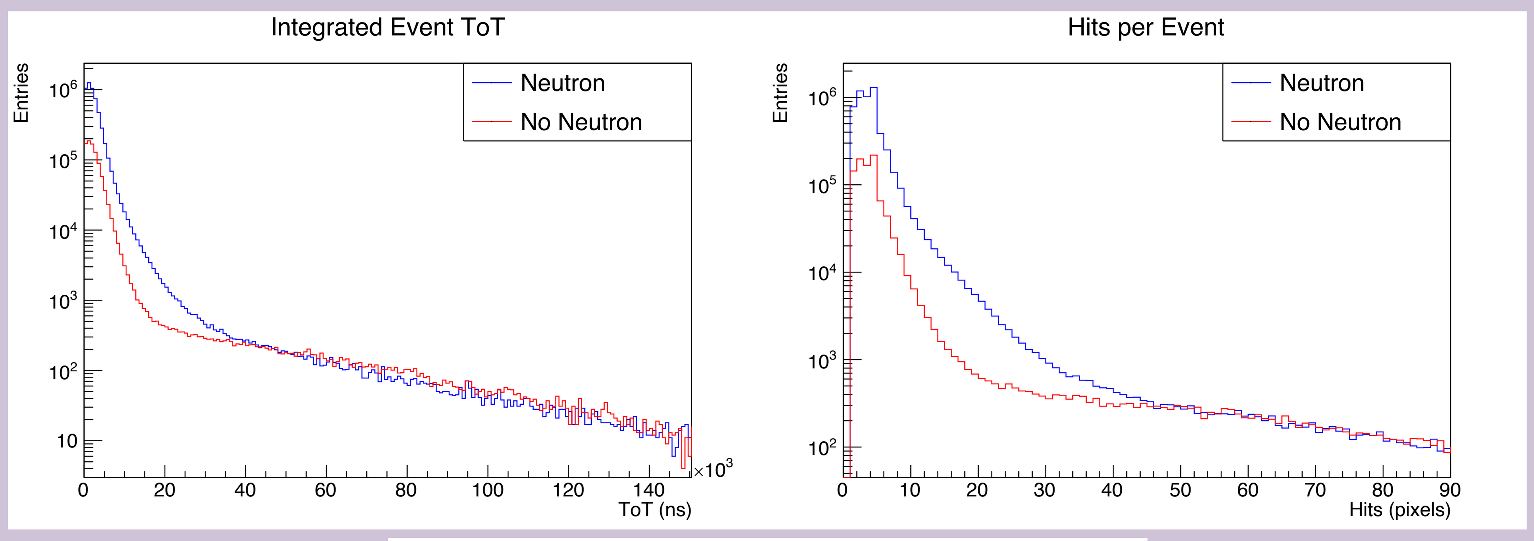


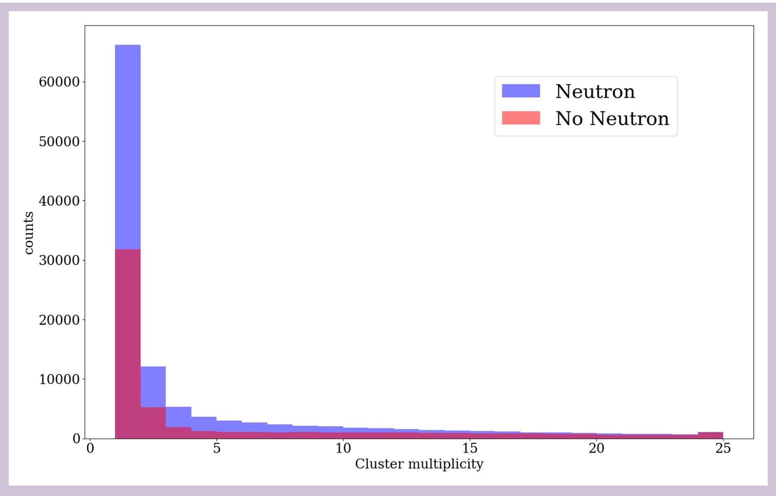
A thermal neutron converts to a maximum of 6 photons. The reconstruction of the photons and the neutrons is:

1. Event (neutron): collection of hits within 40ns from each other.
2. Cluster (photon): hits (in an event) within 20ns fixed time window and maximum 3 pixels apart grouped into clusters.

The bottom plot showing an example event.

Data Analysis





Plots showing (top left) *the integrated event Time over Threshold (ToT)*, (top right) *number of hits per event*, and (bottom center) *number of clusters per event*. Since the energy of the reaction products, alpha or tritium, is only ~ 2.5 MeV, the signal overlaps fully with the background with no distinctive peak.

Pre-cut			
Source	Reconstructed event frequency (Hz)	Minus Background (Hz)	Ratio to maxrate
Detector background	34.2	0	-
Neutron	67.5	33.3	1
Neutron @ 0.5 rate	52.5	18.3	0.55
Neutron @ 0.25 rate	40.8	6.6	0.2

The table lists the *pre-cut event frequency for each dataset*, there are 2 interesting phenomena:

1. The thermal neutron frequency minus the "detector background" is 33.3 Hz, which was higher than the 1 Hz simulated rate. This was caused by the MeV gammas from the source scintillated by the LYSO crystal, this introduces the "source background".
2. The rate of events drops when the source was further away, due to the solid angle. This shows that we are correctly detecting neutrons plus gammas from the source, the rate of both are inversely-proportional to the source's distance.

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. Various parameters were investigated, the most successful ones were:

1. Integrated ToT, $8x10^3 < x < 40x10^3$ (ns). Measured directly from the fitted plot.
2. Number of hits in an event, $15 < x < 50$. Measured directly from the fitted plot.
3. Number of clusters in an event, $1 < x < 9$. This was supported by calculation that each thermal neutron can convert to maximum 6 photon groups.

By cutting using all the above parameters we obtain the following *post-cut event frequency for each dataset.*

Post-cut			
Source	Reconstructed event frequency (Hz)	Minus Background (Hz)	Ratio to maxrate
Detector background	0.8	0	-
Neutron	2	1.2	1
Neutron @ 0.5 rate	1.5	0.7	0.58
Neutron @ 0.25 rate	1.1	0.3	0.25

Conclusion

While using a weak neutron source (simulated rate of < 1 Hz), thermal neutrons were successfully detected using a neutron converter on a scintillator and a portable single photon detector based on Timepix3 and predict the reduced neutron rate. The chosen cutting parameters were effective in suppressing the background due to both the detector setup and the source. The obtained results are therefore a good benchmark for further work.

Future optimizations of the setup in order to maximize upfront the neutron/background discrimination will consider:

- The housing for the lens and scintillator reflects photons internally,
- the lithium layer on the LYSO crystal could reflects photon that was generated away from the camera.

Both effects were not observed in earlier experiments without housing and lithium layer [1].

- The MeV gamma from the AmBe source was a considerable background, a neutron beam would improve the result extensively.

Acknowledgements and References

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