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A hybrid CZT-$LaBr_3$:Ce Compton camera system for improving proton therapy imaging

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Abstract. This work aims to combine the Polaris-J cadmium zinc telluride semi-conductor detector with a $LaBr_3$:Ce scintillation detector as a hybrid Compton camera that can produce high-quality prompt γ ray images. The $LaBr_3$:Ce detectors (Saint-Gobain Crystals) have outstanding timing resolution ($<$ 350 ps), great energy resolution ($<$ 2.5 % at 1332 keV), and a higher maximum energy range. The goal is to use the strengths of the $LaBr_3$:Ce detectors to offset some of the limitations of the Polaris-J detector.

1. Introduction

During proton therapy treatment, the production of prompt γ rays (PG) provides a mechanism for indirectly monitoring proton dose delivery in a patient. Using detection and image reconstruction, prompt γ ray imaging (PGI) aims to provide an in-vivo dose verification technique to improve treatment safety margins [1]. The Polaris-J (H3D Inc., USA) detector has demonstrated potential for improving rage verification techniques, but its limited timing resolution and energy range have hindered its clinical applicability. To overcome these limitations, we propose a novel hybrid Compton camera (CC) system that combines the Polaris-J detector with a fast-timing 2" x 2" $LaBr_3$:Ce detector [2], [3]. This CC aims to improve prompt γ ray imaging precision and accuracy for more reliable treatment planning and delivery in proton therapy.

2. Methodology

In its typical form, a CC is composed of a scatterer and an absorber module. It has the ability to track an incident γ ray as it undergoes Compton scattering in the scatterer module and thereafter fully absorbed in the absorber module, ideally through the photoelectric effect. By recording the energy deposition and interaction positions of these events it is possible to trace the source of the incident γ ray to the surface of a cone-of-origin. Superposition of the reconstructed cones of origin from many events generates an image of the source.

$$cos\theta_1 = 1 + m_e c^2 [\frac{1}{E_0} - \frac{1}{E_0 - E_1}] \quad (1)$$

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Equation 1 is the Compton scatter formula where m_ec^2 is the rest mass of the electron and θ_1 is the angle between the positions of the first and second interactions in the CC. E_0 is the reconstructed γ ray emission energy originating from the target, calculated as the sum of the deposited energy in the scatterer (E_1) and absorber detectors.

Figure 1 shows the configuration of the experiment performed at iThemba LABS, South Africa. A monoenergetic 66.47 MeV proton beam with 1 in 5 pulse selections of 300 ns bunches between pulses at 100 pA was incident on an HDPE encased water target (64 x 64 x 162 mm) situated isocentric with respect to the beam exit and CC. A Polaris-J detector containing two cadmium zinc telluride (CZT) solid-state crystals (20 x 20 x 10 mm), and a 2" x 2" $LaBr_3$:Ce scintillation detector were placed in a CC configuration with the Polaris-J detector as a scatterer, positioned in front of the $LaBr_3$:Ce detector as absorber. The $LaBr_3$:Ce detector was coupled to an R2083 photo-multiplier tube and the output signals of the slow (dyode) and fast (anode) channels were transmitted to a 16-channel digital signal processor XIA Pixie-16 500 MHz module. The software used for the $LaBr_3$:Ce data acquisition (DAQ) was the Multi Instance Data Acquisition System.

Measurements were taken for 20 min during which the Polaris-J detector on-board DAQ was configured to send a synchronization pulse to the $LaBr_3$:Ce detector DAQ in 2 s intervals. These timing pulses were used to align the $LaBr_3$:Ce detector event timestamps with the Polaris-J DAQ time to track double scatters across the two detectors. The measurements were gated on single events from Compton scattering in the CZT crystals. The onboard Polaris-J detector electronics calibrate the spectra allowing for real-time spectrum viewing. The $LaBr_3$:Ce detector was energy calibrated by using the known peaks in the spectra of ^{152}Eu and AmBe sources, along with the 1470 keV ^{138}Ba peak which comprises part of the detector internal radiation due to the ^{138}Ce dopant.

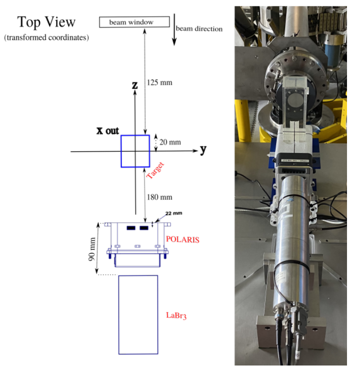

Figure 1. Experiment configuration with a schematic is shown to the **left**, and a photograph to the **right**.

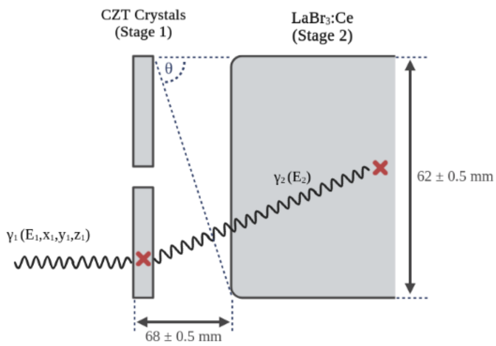

Figure 2. Schematic of the setup which tracks an emitted γ ray across the two-stage CC.

3. Results

Compton scatters of the PG in the Polaris-J detector followed by the photoabsorption of the scattered γ rays in the $LaBr_3$:Ce detector (E_2) allow for the energy reconstruction of $E_0 = \Delta E_1 + \Delta E_2$, producing the known proton-induced oxygen and carbon peaks in the energy spectra originating from the water target. Figure 3 shows the calibrated energy spectra of the two detectors with the labeled PG peaks. Previous studies have shown that specific γ ray emission lines from carbon and oxygen are strongly correlated to the proton depth dose distribution and can be used for PGI [4], [5].

When comparing the events recorded by each detector, the Polaris-J triggered a third of the events. The delayed triggering time of the Polaris-J detector has been investigated by [6] where it was found that when a photon interaction (> 50 keV) produces an output signal, the detector enters a triggered state of 1.5 μs during which new interactions are able to be recorded, however, after the trigger state, a variable dead state lasting $15 - 300$ μs begins. For the duration of the dead state, no new events are recorded. A variable timing window will be implemented to allow for greater accuracy in tracking the double scatter events across detectors. This timing window is currently being quantified by investigating a delay trend in the timing difference between events recorded across the CC detectors within beam bunch time.

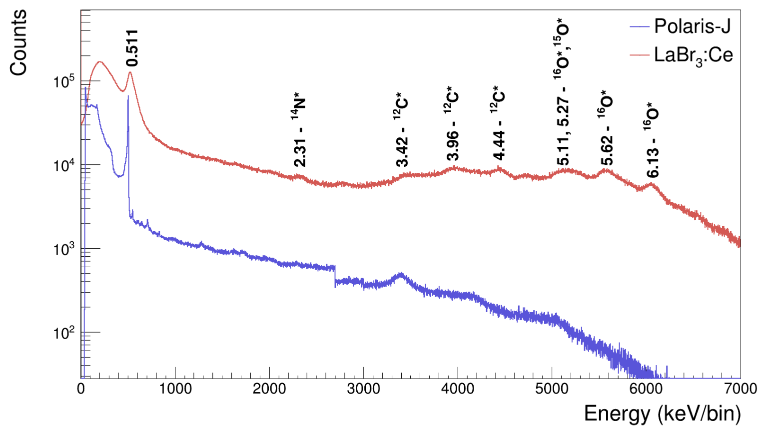

Figure 3. Energy spectra from the Polaris-J and $LaBr_3$:Ce detectors. Labeled (in units of MeV) are the PG emission lines and their single and double escape peaks from the major constituent elements of the water target.

4. Conclusions and Future Work

The time synchronization of the $LaBr_3$:Ce detector with the Polaris-J detector, followed by the application of a timing window to account for the different timing capabilities of the two detector systems represents a first step toward the development of a hybrid CC with a novel way to improve the quality of double γ ray scatter events. Double γ ray scatters are traceable across the CC setup. Future work will be focused on using the principles of the Compton scatter equation in the form of the Compton line filtering technique to further reduce nonphysical double scatter events by removing events whose E_1 and θ_1 values do not match those predicted by the Compton equation. With CLF applied, the remaining doubles are identified as good scatter events that correspond to the theoretical Compton scattering predictions and can be used for image reconstruction.

Acknowledgments

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