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Measurement of angular correlations of Compton-scattered gamma quanta from positron annihilation using GAGG:Ce scintillator matrices with single-side readout

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Abstract: We measured azimuthal correlations of the Compton-scattered gamma quanta from positron annihilation with two 8 × 8 matrices of Gadolinium Aluminum Gallium Garnet doped with Cerium. Each detector matrix contains 64 crystals of size 3 mm × 3 mm × 20 mm and it is read-out by a single Silicon Photo-multiplier (SiPM) array, with one SiPM matching one pixel. The studied single-side readout concept keeps the modules compact and cost-efficient on a large scale. Coincidence events were recorded using a Na-22 source placed between the modules. We clearly identify and reconstruct the Compton scattering events and we observe the excess of orthogonally scattered gammas over the ones with the parallel azimuthal angles. We present the measured azimuthal modulation factors for several kinematic selection criteria and different inter-pixel distances.

Keywords: Compton imaging; Gamma camera, SPECT, PET PET/CT, coronary CT angiography (CTA); Gamma detectors

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1 Introduction

In-silico studies have shown that utilization of polarization correlations of positron annihilation quanta can potentially enhance imaging quality in Positron Emission Tomography (PET) [1–3]. If orthogonally polarized gammas emitted following positron annihilation undergo Compton scattering, the orthogonality of their polarizations will reflect, with a high probability, in orthogonality of their azimuthal scattering angles, which offers a handle, independent of energy, to identify true coincident events in PET. However, to date this has not been implemented in biomedical imaging.

Experimentally, it has been demonstrated that the angular correlations, manifested via Compton scattering, can be measured using single-layer detectors which may eventually lead to realistic and cost-effective PET apparatus [4]. In the present work, we explore the performance of a pair of single-layer detector modules, based on Gadolinium Aluminum Gallium Garnet doped with Cerium (GAGG:Ce) in detecting the azimuthal correlations of annihilation quanta. The Compton scattering events are successfully identified and reconstructed and we present the measured azimuthal modulation factors for several kinematic selection criteria and different inter-pixel distances.

2 Methodology

Two detector modules consisting of 8×8 matrix of GAGG:Ce scintillator crystals (Hilger Crystals Ltd., UK) and a matching SiPM array (Hamamatsu Photonics, Japan, model S13361-0808AE) were assembled. Each matrix contained 64 crystals with a size of 3 (mm) $\times$ 3 (mm) $\times$ 20 (mm). All crystal sides were polished with the 0.2 mm reflector between the crystals, resulting in a matrix pitch of 3.2 mm. The measurements using a Na-22 source ($\approx$1 μCi) placed equidistantly 4 cm from each module, were carried out at an over voltage (V_{OV}) of 4.0 V at temperatures $\approx$18° ± 1°C. The spectrum obtained from each pixel was individually calibrated and corrected for non-linearity. We obtained the mean energy resolution at 511 keV of 9.7% ± 0.2% and 11.2% ± 0.1% for the two modules, respectively [5]. The coincidence data were acquired using the TOFPET2 system with the default configuration [6]. The Compton events that occurred in a module are selected requiring the sum of the fired pixel energies to be within $\pm 3\sigma$ from the 511 keV peak maximum. This energy must be shared between exactly two fired pixels. A lower bound of 70 keV for pixel energies in one module and 120 keV in the other module is set to avoid possible noise contributions. The Compton scattering angle θ in each module is deduced from Compton scattering kinematics: $\theta = a\cos[m_e c^2(1/E_\gamma - 1/E_{\gamma'}) + 1]$, where E_γ and $E_{\gamma'}$ are the energies of the initial and the scattered gamma, respectively. We assume the pixel with the lower energy corresponds to the recoil electron, since the cross-section and the detector configuration favor forward scattering. The simulations show that this is justified in $\approx$60% of events [7]. The azimuthal angle ϕ is reconstructed using the positions of the fired pixels according to: $\phi = a\tan(\Delta x/\Delta y)$, with Δx and Δy being the distances of the pixel centres in the x–y plane (perpendicular to the longer crystal axis). In further analysis we select the events in which both quanta undergo Compton scattering with angles $\theta_{1,2}$ and $\phi_{1,2}$, respectively. The sensitivity of the measurement to the initial polarization correlations of annihilation quanta is characterized by the modulation factor, μ, determined by fitting the acceptance-corrected distribution of azimuthal angle differences, $N_{\mathrm{cor}}(\phi_1 - \phi_2)$, with the function [4]:

$$N_{\mathrm{cor}}(\phi_1 - \phi_2) = M[1 - \mu \cos(2(\phi_1 - \phi_2))]. \tag{2.1}$$

The corrected acceptance $N_{\mathrm{cor}}(\phi_1 - \phi_2)$ is calculated as, $N(\phi_1 - \phi_2)/A_n(\phi_1 - \phi_2)$, where $A_n(\phi_1 - \phi_2)$ is obtained by the event-mixing technique [4], where, ϕ_1 and ϕ_2 are taken from different events.

3 Results and discussion

We explored the μ dependence on $\theta_{1,2}$ range, as well as its dependence on the average azimuthal resolution, $\langle\Delta\phi\rangle$ varied by selecting pixel pairs with distances, $d_{1,2}$, where $d_{1,2}$ is the distance between the events projected onto the face of the detector 1 and 2, respectively. Examples of obtained distributions of $N_{\mathrm{cor}}(\phi_1 - \phi_2)$ are plotted in figure 1 while the full results are listed in table 1. The observed modulation factors are consistently higher for $72^\circ < \theta_{1,2} < 90^\circ$ than for $60^\circ < \theta_{1,2} < 80^\circ$ consistent with the theory, which predicts the highest modulation close to $\theta_{1,2} = 82^\circ$ [8]. The rise of the sensitivity is observed when the azimuthal resolution drops from $\langle\Delta\phi\rangle \approx 24^\circ$ to $\langle\Delta\phi\rangle \approx 17^\circ$ (data sets 1–3), which is expected since the effective modulation factor is averaged over a narrower angular range [9]. However, μ remains constant with further improvement of the azimuthal resolution (data sets 4–6), signaling that the energy resolution becomes the governing factor of the sensitivity. The findings are comparable with a previous study using LFS crystal matrices with only slightly lower energy resolution of 12.2% at 511 keV [4].

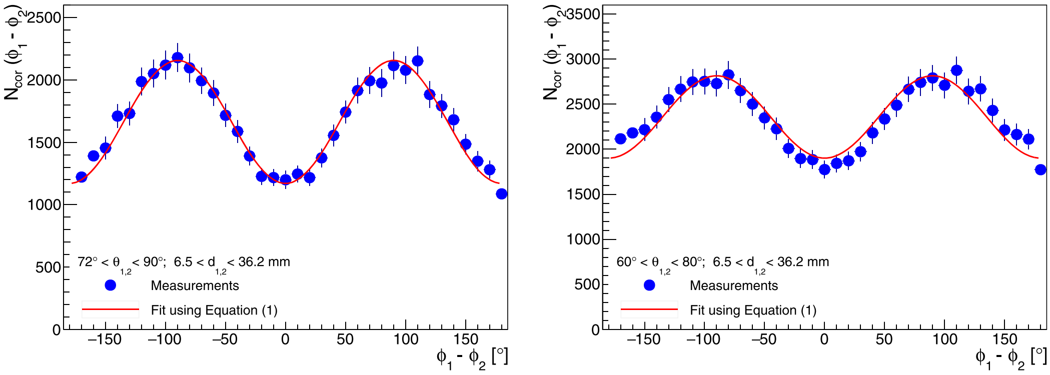

Figure 1. The acceptance corrected $(\phi_1 - \phi_2)$ distributions for pixel distances $6.5 \leqslant d_{1,2} \leqslant 36.2$ mm at (left) $72° \leqslant \theta_{1,2} \leqslant 90°$ and (right) $60° \leqslant \theta_{1,2} \leqslant 80°$.

Table 1. Modulation factor μ for different scattering angles; different pixel distances $d_{1,2}$ and the corresponding mean azimuthal resolutions $\langle\Delta\phi\rangle$.

Set No.	Distance	$72° \leqslant \theta_{1,2} \leqslant 90°$		$60° \leqslant \theta_{1,2} \leqslant 80°$	
	$d_{1,2}$ (mm)	$\langle\Delta\phi\rangle$	μ	$\langle\Delta\phi\rangle$	μ
1	$3.3 < d_{1,2} < 36.2$	23.3°	0.26 ± 0.01	24.3°	0.14 ± 0.02
2	$4.6 < d_{1,2} < 36.2$	18.8°	0.28 ± 0.01	19.2°	0.17 ± 0.02
3	$6.5 < d_{1,2} < 36.2$	17.4°	0.30 ± 0.01	17.6°	0.18 ± 0.02
4	$7.2 < d_{1,2} < 36.2$	14.3°	0.28 ± 0.02	14.4°	0.19 ± 0.02
5	$9.1 < d_{1,2} < 36.2$	13.7°	0.29 ± 0.02	13.7°	0.19 ± 0.02
6	$9.7 < d_{1,2} < 36.2$	13.1°	0.29 ± 0.02	13.2°	0.19 ± 0.02

4 Conclusions

We successfully measured polarization correlations of annihilation quanta with two single-layer GAGG:Ce 8 × 8 matrices. The modulation factors are the largest for Compton scattering angles $\theta_{1,2} \approx 82°$, and they improve around $d_{1,2} = 6.5$ mm reaching $\mu = 0.30 \pm 0.01$. The results show that a further improvement of the energy and angular resolution may result in even better polarimetric performance. The discrimination of correlated vs. non-correlated events in PET may be utilized to further distinguish the signal and the background, respectively, while the simplicity of the single-layer concept enables its cost-efficient application on a larger scale.

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