Measurement of Scattering Azimuthal Distribution of Polarized Gamma-Rays in Compton Scattering Using GAGG(Ce) Scintillator

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1. Introduction

Recently, the measurement of gamma-rays polarization has increasingly become important for applications in various fields such as astrophysics measurements and medical imaging. In this study, we fabricated the gamma-rays polarization detector using $Gd_3Ga_2Al_3O_{12}$ (Ce) scintillator, in short GAGG, which has high sensitivity, energy resolution and stability, and measured the gamma-rays polarization in MeV range, assessing performance of the detector.

2. Materials and Methods

▪ Principle of measuring gamma-rays polarization

The most general way for polarization measurement is utilizing the formula of differential cross section in Compton scattering, called Klein-Nishina formula,

$$\frac{d\sigma}{d\varphi} = A + B\cos(2\varphi) \quad \dots \quad (1)$$

where φ represents the scattering azimuthal angle from polarization direction of gamma-rays, and the others are constant values. Based on this formula, we can estimate the gamma-ray polarization through the distribution of azimuthal angle φ.

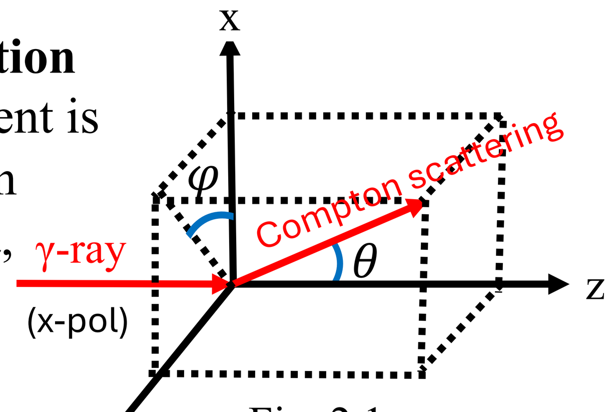

Fig. 2.1

▪ Detector fabrication

For detecting φ angle, we fabricated the detector mainly consisting of scatterer and absorber, each of which uses GAGG array (Fig. 2.2). This GAGG array is pixelated 8 × 8 with a single pixel size of 2.5 mm × 2.5 mm. We used 1 piece of GAGG with 4 mm thickness for scatterer, and 8 pieces with 9 mm thickness for absorber. These 8 set of GAGG arrays in absorber were placed 5 cm away from the scatterer in a circular pattern with 5 cm radius parallel to scatterer to detect scattering azimuth angle (Fig. 2.3, Fig. 2.4). Then, each GAGG array was attached with 8 × 8 Multi-Pixel Photon Counter (MPPC) array for detecting photons from GAGG pixel.

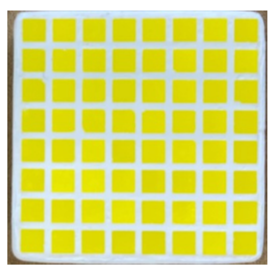

Fig. 2.2

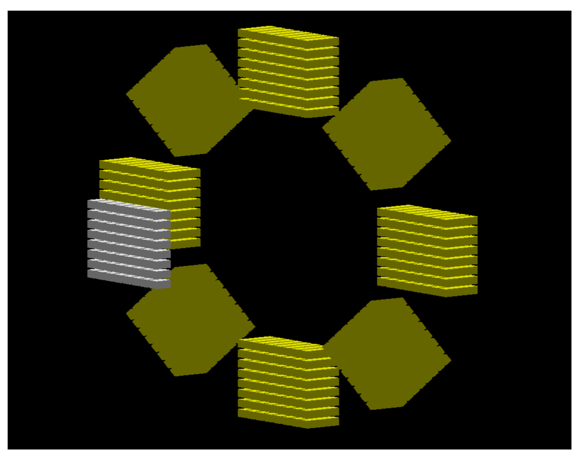

Fig. 2.3

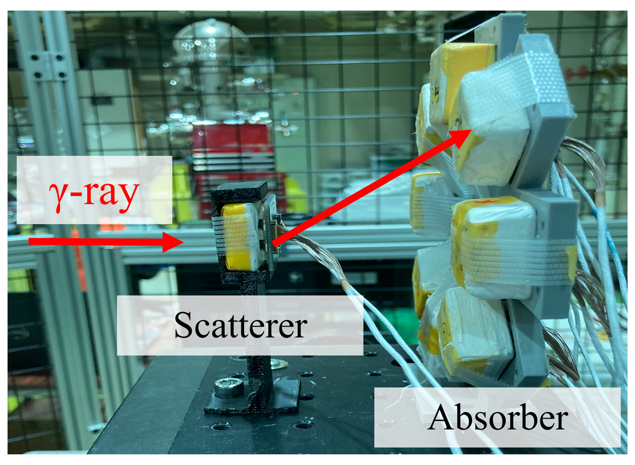

Fig. 2.4

▪ Beamline

For polarized gamma-rays irradiation, we used B1LU beamline in Ultraviolet Synchrotron Orbital Radiation Facility (UVSOR) with 6.6 MeV energy and 1 kHz frequency, which can control polarization. We irradiated 0°, 45°, 90°, and circular polarization gamma-rays to the center of the scatterer for 210 minutes.

3. Data acquisition system

▪ MPPC signal processing

For processing signal from MPPC, we used dynamic time over threshold (dToT) method. In this way, we can get ToT width signal through comparator which is more linear to energy than conventional ToT method (Fig. 3.1). This processing was conducted by circuit on the board, called dToT board, and each dToT board was connected to each MPPC array (64ch).

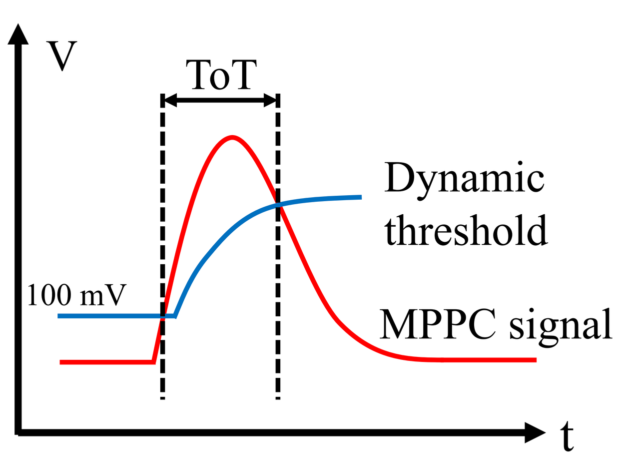

Fig. 3.1

▪ Data acquisition and transfer

We used Field Programmable Gate Array (FPGA) circuit system, called PETnet for data acquisition and transfer, which operates at 8 GHz. This system handles the data from dToT board on ToT width, timing, and pixel number, and conveys these data in 8-byte binary format to the PC via LAN hub.

▪ Beam trigger signal

To determine the timing of the gamma-ray beam, we got beam trigger signal from beamline machine as an input of dToT board. This signal was square wave with 3 V pulse height, and the duration time was about 100 ns.

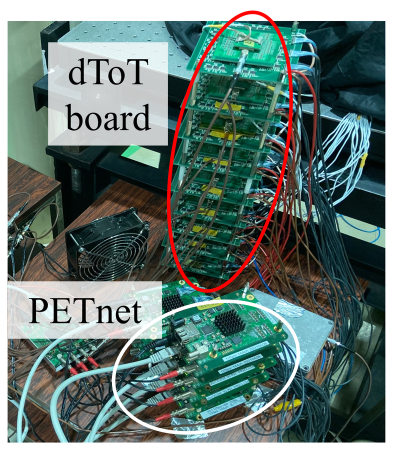

Fig. 3.2

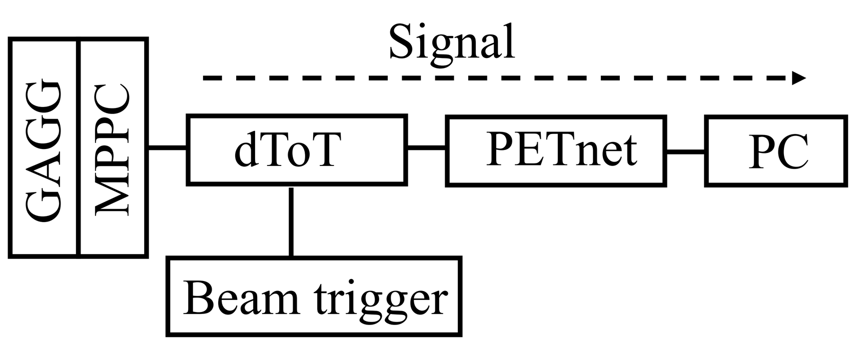

Fig. 3.3

4. Analysis and Result

▪ Time coincidence

To find the Compton scattering event between scatterer and absorber, we imposed the condition on scatterer that the signal was detected within 80 ns to 200 ns from beam trigger signal, and on absorber that the signal was within 100 ns from the nearest scatterer signal. The time coincidence distribution is shown in Fig. 4.1 and Fig. 4.2.

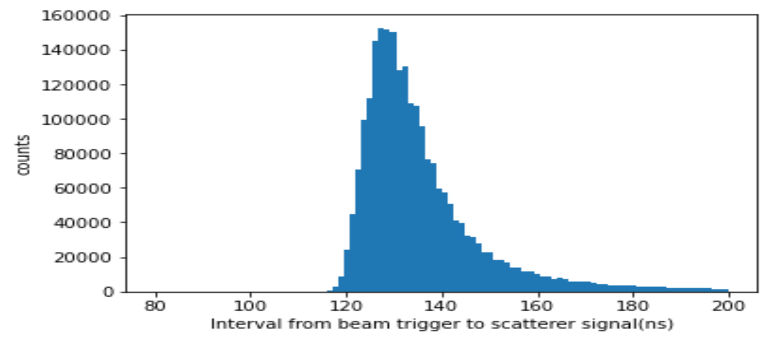

Fig. 4.1

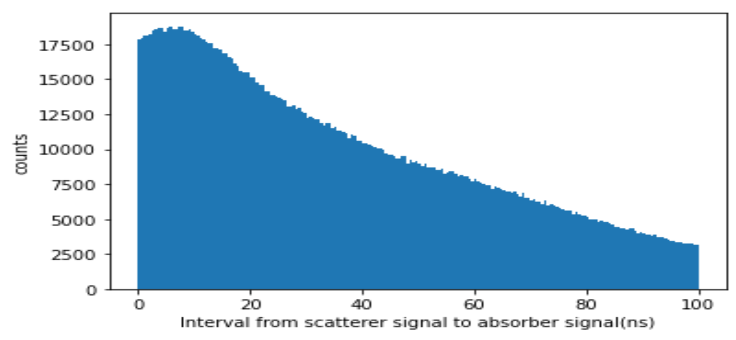

Fig. 4.2

▪ Energy spectrum

The energy spectrum is shown in Fig. 4.3 and Fig. 4.4. These energy was calculated from ToT through energy calibration of ^{85}Sr and ^{137}Cs.

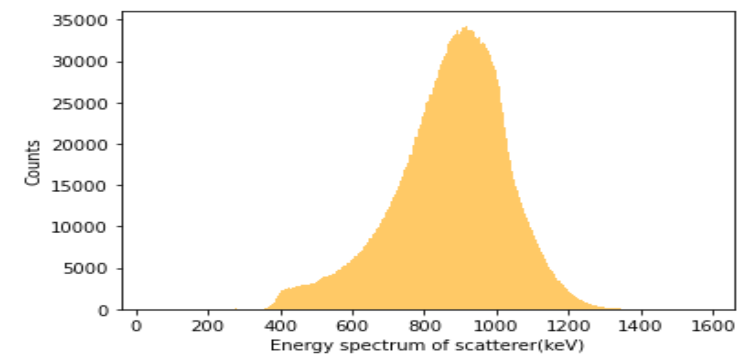

Fig. 4.3

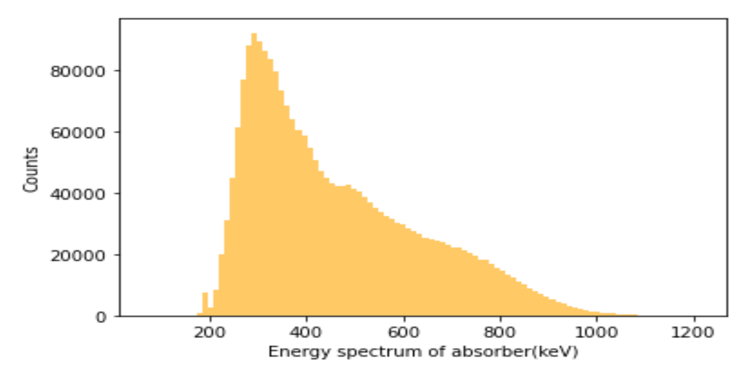

Fig. 4.4

▪ Scattering azimuthal distribution

After the event selection above, the total number of true event for each GAGG array was calculated and mapped to scattering azimuthal angle φ in 45 ° increments. Then, we adjusted the counts of 0°, 45°, 90° using those of circular polarization, fitted with cosine curve based on formula (1). The phase errors, relating to the prediction capacity of polarization, were -2.5°, +1.1°, +7.9° respectively. Also, the modulations, defined as $\frac{N_{max}-N_{min}}{N_{max}+N_{min}}$ and meaning the sensitivity to polarization, were 2.2%, 2.1%, 1.7%, while those in Geant4 simulation were 3.7%, 3.7%, 4.1%.

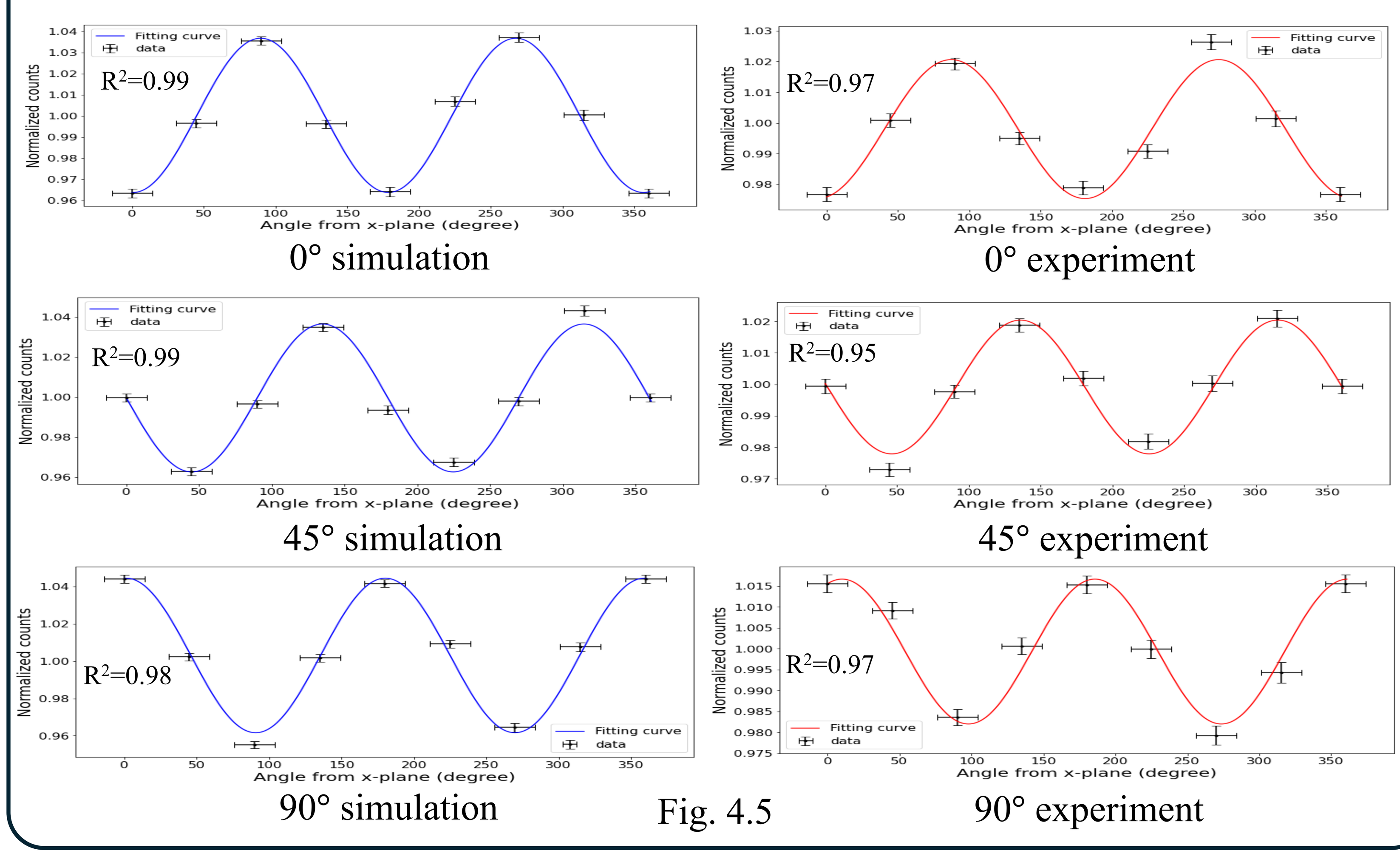

Fig. 4.5

5. Conclusion

In summary, we fabricated the gamma-rays polarization detector using GAGG and assessed the performance for MeV region, which indicates our detector has sensitivity to gamma-rays polarization. For future works, it seems crucial to reflect more deeply on the detector geometry to enhance the performance. Also, it is necessary to try with lower energy polarized gamma-rays considering the application for biology field such as medical imaging.

6. Reference

1. Klein.O, Nisina.Y : Über die Streuung von Strahlung durch freie Elektronen nach der neuen relativistischen Quantendynamik von Dirac.
2. P.Moskal, , N. Krawczyk, B. C. Hiesmayr, et al : Feasibility studies of the polarization of photons beyond the optical wavelength regime with the J-PET detector.