Detection of Gamma Ray Polarization Using a 3-D Position-Sensitive CdZnTe Detector

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***Abstract*—When a polarized gamma ray photon undergoes a Compton scatter, the probability for the photon to scatter at a fixed scattering angle depends on the azimuthal angle. The polarization of incident gamma rays can be measured using this effect by observing the angular distribution of scatters. Room-temperature 3-dimensional position-sensitive CdZnTe detectors can provide good energy resolution as well as positions of interactions, allowing these detectors to perform Compton imaging and polarization detection simultaneously. In this paper, we demonstrate that an 11×11 pixellated $15 \times 15 \times 10\ \mathrm{mm}^3$ CdZnTe detector with 3-D position sensing capability can be an effective instrument to detect the polarization of incident gamma rays.**

***Index Terms*—Compton scattering, Gamma-ray polarization 3-D position sensitive CdZnTe detector.**

I. INTRODUCTION

THE polarimetry of X-ray or gamma-ray sources is an important tool to investigate the process of X-ray or gamma ray production in high-energy astrophysics. With the recent report of linear polarization in the prompt gamma-ray emission from gamma-ray burst GRB021 206 [1], which provided detailed information of the origin of gamma-ray bursts (GRB), interest has risen in polarimetry in high-energy astrophysics [2]. The current X-ray or gamma-ray detectors employed for astrophysics missions are not optimized for polarization study, and polarimetry ability is one of the most interested characteristics for next-generation X-ray and gamma-ray telescopes. In 1996, Inderhees and Kroeger successfully demonstrated the detection of the polarization of gamma rays using position-sensitive germanium strip detectors (GSD) [3], [4]. However, the cooling requirement of germanium detectors is a serious limitation for satellite missions. In this paper, we show that room-temperature three-dimensional (3-D) position-sensitive CdZnTe detectors, which are designed for gamma-ray spectroscopy and imaging [5]–[7], can be an excellent candidate to do polarization measurements.

The three most important interactions of X-rays and gamma-rays with matter are all polarization dependent. The direction of the products from these interactions, i.e., photoelectrons in photoelectric absorption, scattered photons in Compton scattering, and electron-positron pairs in pair production, all retain signatures of the polarization information of the incident photons. This angular dependence on the polarization direction of the incident photons can be the basis of the polarization measurement in different energy ranges. For soft gamma-rays with energy between 300 keV and 10 MeV, Compton scattering is the dominant process and is the most-used interaction in current polarization measurements.

According to the Klein-Nishina formula, the Compton scattering cross section for a linearly polarized gamma ray is

$$d\sigma = \frac{r_0^2}{4} d\Omega \frac{k_1^2}{k_0^2} \left[\frac{k_0}{k_1} + \frac{k_1}{k_0} - 2\sin^2\theta\cos^2\eta \right] \tag{1}$$

in which $d\sigma$ is the differential cross section, $d\Omega = \sin\theta d\theta d\eta$ is the differential solid angle around Ω, r_0 is the classical electron radius, k_1 and k_0 are the respective momenta of the scattered and initial gamma rays, θ is the scattering angle, and the azimuthal angle η is the angle between the electric vector of the incident gamma ray and the scattering plane. As a result, for any specific scattering angle, the scattering probability is maximized when $\eta = 90^\circ$, which means the scattered photon prefers to be ejected at directions perpendicular to the polarization plane of the incident photon. By measuring the azimuthal angular distribution of the scattered photons, the polarization information of the incident photons can be deduced.

To quantify the polarization information, the modulation ratio is defined as

$$R(\varphi) = \frac{n(\varphi) - n\left(\varphi + \frac{\pi}{2}\right)}{n(\varphi) + n\left(\varphi + \frac{\pi}{2}\right)} \tag{2}$$

where φ is an arbitrary angle in a plane perpendicular to the incident photon direction, and $n(\varphi)$ is the measured number of events in $d\phi$ about that angle.

Suppose the polarization direction of the incident gamma rays is at φ_0, then $\eta = \varphi - \varphi_0$

$$\begin{aligned} R(\varphi) &= \frac{n(\varphi) - n\left(\varphi + \frac{\pi}{2}\right)}{n(\varphi) + n\left(\varphi + \frac{\pi}{2}\right)} \\ &= \frac{\sigma|_{\eta=\varphi-\varphi_0} - \sigma|_{\eta=\varphi+\frac{\pi}{2}-\varphi_0}}{\sigma|_{\eta=\varphi-\varphi_0} + \sigma|_{\eta=\varphi+\frac{\pi}{2}-\varphi_0}} \\ &= \frac{-\sin^2\theta\cos(2\varphi - 2\varphi_0)}{\frac{k_0}{k_1} + \frac{k_1}{k_0} - \sin^2\theta} \end{aligned} \tag{3}$$

in which $\sigma|_\eta$ is the Compton scattering cross section at η. As we can see, at each scattering angle θ, the modulation ratio is a sinusoid function of $\cos(2\varphi - 2\varphi_0)$, which has a period of π. The amplitude of the modulation ratio versus the energy of incident photons and scattering angle is shown in Fig. 1. Since the phase of the modulation ratio is independent of θ, the average

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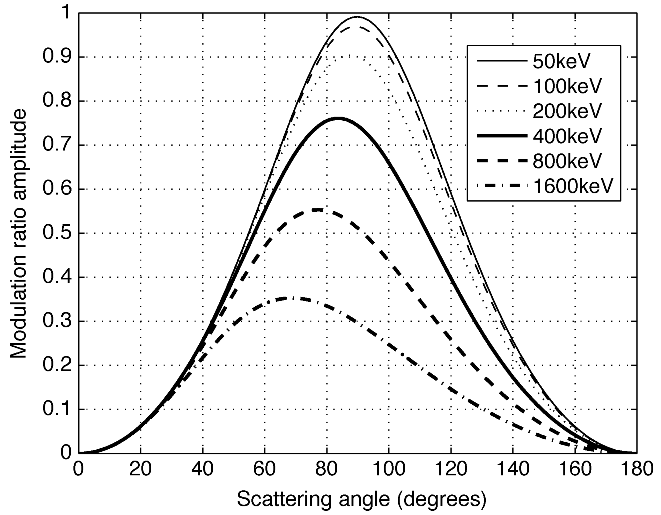

Fig. 1. The change of the modulation ratio amplitude according to different incident gamma ray energies and scattering angles. For a fixed incident gamma ray energy, the modulation ratio amplitude is maximized when the scattering angle is slightly less than 90°.

modulation ratio over all scattering angles is still a function of $\cos(2\varphi - 2\varphi_0)$. The modulation ratio is maximized when φ is perpendicular to the polarization plane of the incident photon ($\varphi = \varphi_0 + \pi/2$), and is minimized when φ is along the polarization plane ($\varphi = \varphi_0$). Therefore, the polarization direction and degree can be deduced from the measured phase and amplitude of the modulation ratio, respectively.

II. DETECTOR

The 3-D position-sensitive CdZnTe detector is $15\ \mathrm{mm} \times 15\ \mathrm{mm} \times 10\ \mathrm{mm}$ in dimension and the anode is pixellated into an 11 × 11 array, so the position uncertainty is about 1.2 mm in lateral directions. The interaction depth is obtained by measuring the electron drift time from the interaction position to the pixel anode (Fig. 2). The depth resolution is about 1 mm. The detector used in this polarization measurement was coupled to the second-generation ASICs (VAS2TAT2) and the energy resolution at 662 keV is 1.1% and 1.6% for single and double pixel events, respectively [6]. The 3-D position-sensing capability enables the 3-D CdZnTe detector to perform Compton imaging, as well as polarization measurement.

To obtain a polarized gamma-ray source, 662 keV photons from a $^{137}\mathrm{Cs}$ source were scattered 90° by a $25.4\ \mathrm{mm} \times 25.4\ \mathrm{mm}$ BaF_2 scintillator before entering the detector. The scintillator and the CdZnTe detector were operated in coincidence to suppress the background. The 90°-scattered photons irradiated the CdZnTe detector from the cathode side. From theoretical calculations, those photons were 58% polarized (see the Appendix). In the actual experiment configuration shown in Fig. 3, due to the finite size of the scintillator, the photons entering the CdZnTe detector were not exactly 90° scattered. Therefore, the polarization degree of the incident photons was slightly less than 58%, which is one of the reasons causing the deficiency of the simulated modulation ratio when compared with the theoretical value (Fig. 4). When changing the position of the $^{137}\mathrm{Cs}$ source, the polarization direction of the scattered photons will change accordingly.

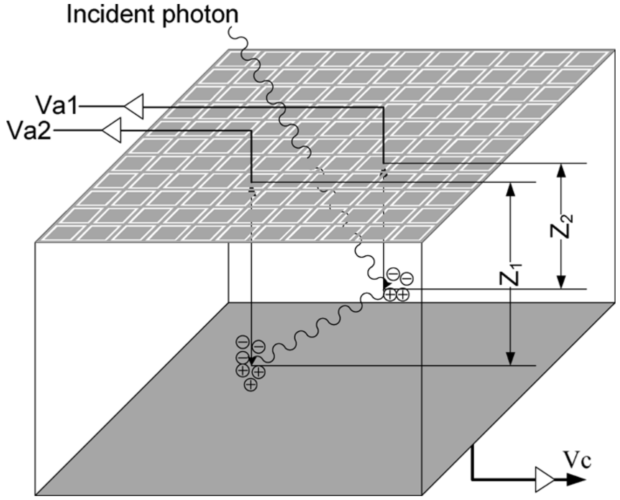

Fig. 2. Three–dimensional position-sensitive CdZnTe detector. The lateral position is given by the location of individual pixels collecting electrons, and the interaction depth is obtained by measuring the drift time of electrons from the interaction location to the collecting anode.

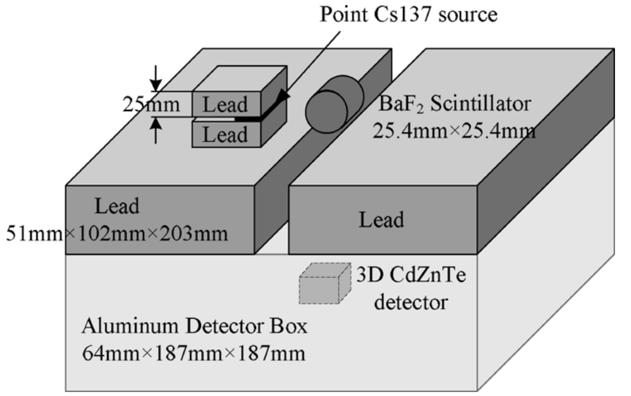

Fig. 3. Experimental setup. The $^{137}\mathrm{Cs}$ source was scattered by the BaF_2 scintillator before entering the CdZnTe detector. The scintillator was operated in coincidence with the CdZnTe detector to suppress the background. The CdZnTe detector is enclosed in the detector box and placed underneath the scintillator.

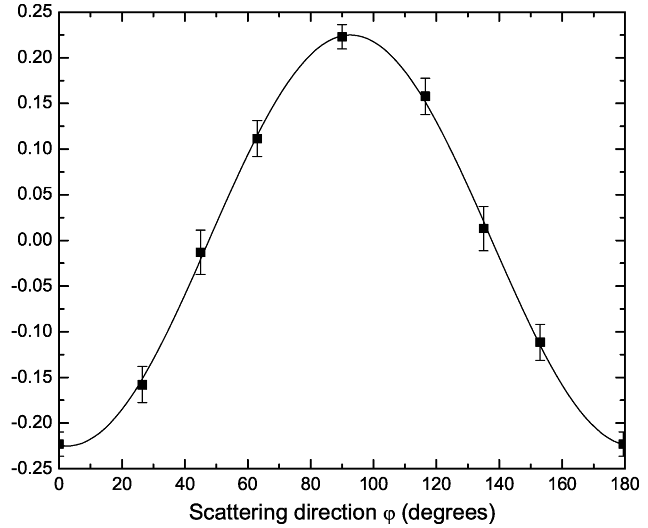

Fig. 4. The modulation ratio from simulation. The amplitude of the modulation ratio is 0.225, which is slightly less than the theoretical value of 0.24. The difference is caused by the finite size of the scintillator, the different detection efficiencies for different scattering angles and the finite pixel size.

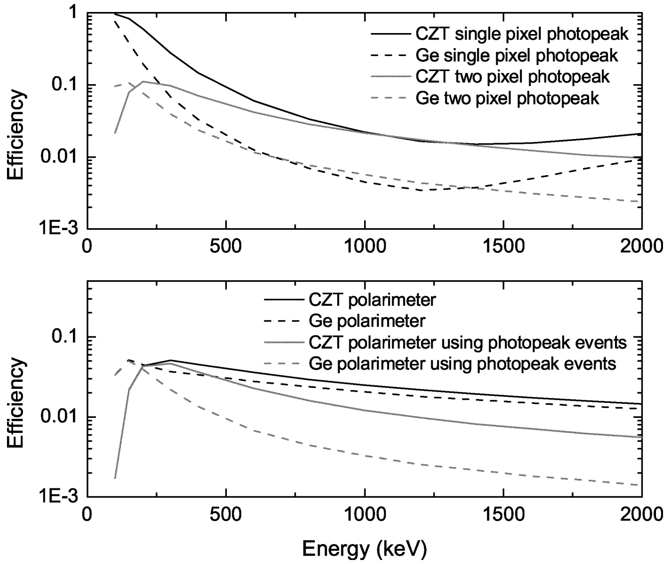

Fig. 5. Simulated spectrometer and polarimeter efficiencies for CdZnTe and Ge detectors. The events useful for polarimeter are defined as nonneighboring two-pixel events.

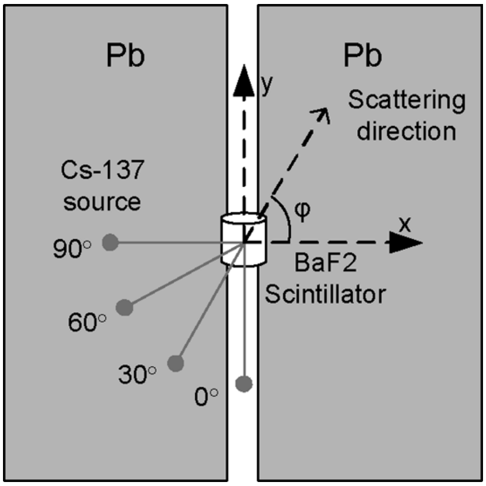

Fig. 6. Top view of the measurement setup. The source was placed at four different locations to produce scattered gamma rays with different polarization directions, which can be deduced by measuring the distribution of the scattering direction in the CdZnTe detector. The CdZnTe detector was placed underneath the BaF_2 scintillator and is not displayed in this figure.

This will be reflected by the phase change of the measured modulation ratio.

III. SIMULATIONS

Theoretical calculation gives the amplitude of the modulation ratio to be 0.238 if all Compton scatters are recorded (see the Appendix). From (3) and Fig. 1, the modulation ratio is a function of the scattering angle. In the actual detector system, the detection efficiency will vary at different scattering angles, therefore the measured amplitude of the modulation ratio depends on the geometry of the detector. However, in this experiment, due to the low incidental gamma-ray energy, the detection efficiency at different scattering angles will be very close to 100%, except those scattering events with very large or small scattering angles (those events will deposit two interactions under a same pixel and will not be recorded as two pixel events by the detector system). Therefore, the measured modulation ratio should be still close to the theoretical value. In addition, since the detector is pixellated, the measured count rate at a specific scattering direction inside the CdZnTe detector depends on the solid angles subtended by pairs of pixel anodes along that scattering direction, which will contribute to the decrease of the amplitude of the modulation ratio. Simulations were run using the Geant Monte Carlo package to account for the effect of the detector geometry.

As we can see in Fig. 4, the simulated amplitude of the modulation ratio is slightly less than the theoretical calculation.

Simulations were also run to study the efficiency of the 3-D CdZnTe detector as a polarimeter. In the simulation, the detector was irradiated by a beam of linearly polarized photons from the cathode side. For comparison, a Ge detector with the same geometry was also simulated. The polarimeter efficiency was calculated using only nonneighboring two-pixel events. For incident gamma rays with energy greater than 200 keV, the results in Fig. 5 show that CdZnTe detector has higher efficiency although the Compton scattering cross sections of CdZnTe and germanium are very close to each other. The advantage of CdZnTe is more significant if only photo peak events are selected for polarization measurement. This is because that CdZnTe has more stopping power for the scattered photon due to higher photoelectric cross section.

IV. MEASUREMENTS

As shown in Fig. 6, the ^{137}Cs source was placed at four different locations, which are at 0°, 30°, 60°, and 90° with respect to the direction of the gap. Events recorded by two neighboring anode pixels on the 3-D pixellated CdZnTe detector were excluded to eliminate the influence of charge sharing events. The activity of the ^{137}Cs source was 20 μCi. The count rate of two-pixel events in the detector was very low. After one week of data acquisition, only about 3500 useful events were recorded. The observed events were mostly recorded by two anode pixels that are separated only by one pixel in between, thus, the recorded scattering direction can only have some discrete values, such as 0°, 27°, 45°, 63°, and 90°.

The polarization direction of the scattered photons will change according to the position of the ^{137}Cs source. This will be reflected by the phase change of the measured modulation ratio as shown in Fig. 7. The modulation ratio should have a period of 180°, and any two points with 90° phase difference should differ only in the sign.

The low count rate has contributed to the large experimental uncertainties. However, the phase change in the modulation ratio is still evident. The amplitude of the modulation ratio is between 0.19 and 0.25, which is close to the theoretical value of 0.238. The statistical uncertainties of the measurement should be improved if more counts are collected.

The 3-D position-sensitive CdZnTe detector can provide both the energy and position information of individual gamma ray interactions. Thus, the source location can be reconstructed by means of Compton imaging. Since the incident direction of gamma rays from a source can be identified, the polarization measurement can be performed on any source in space. To

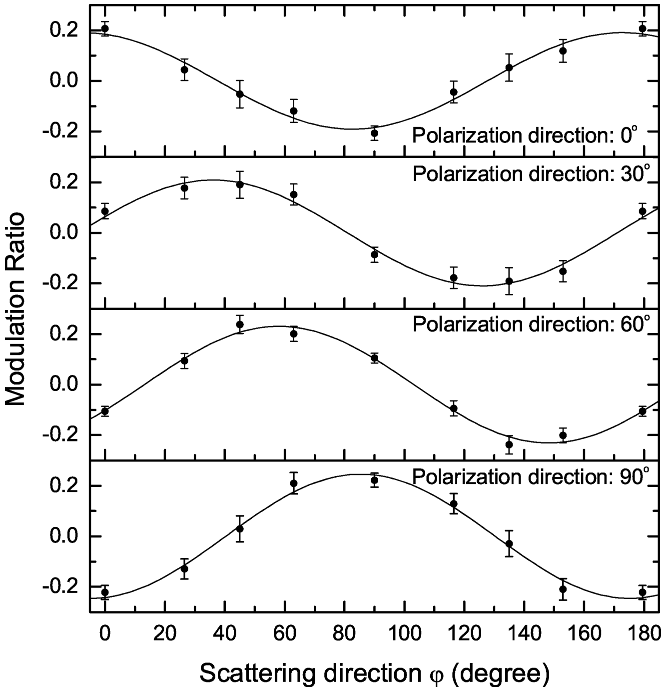

Fig. 7. Modulation ratio measured for 288 keV gamma rays with 60% polarization degree. The phase shift of the modulation ratio reflects the measured polarization direction, and the amplitude of the modulation ratio is proportional to the polarization degree.

demonstrate this capability, image reconstruction was performed using one of the measured data sets with list-mode maximum-likelihood algorithm [8]–[10], which showed the source correctly at the location of the $\mathrm{BaF_2}$ scintillator (Fig. 8), where the incident photons were originated.

In our data processing program, events with all scattering angles were taken into account to provide better statistics. From Fig. 1, we can see that the modulation ratio is maximized at scattering angle slightly less than 90°. If a specific range of scattering angles around 90° is selected to enhance the polarization effect, higher modulation ratio should be achieved. The selection of scattering angles can be done by selecting scatter energies, positions of interactions, or even both to provide better accuracy by rejecting those non-Compton scattering events, such as events with multiple interactions under one pixel anode or events produced by pair production at higher energies. However, to get the scattering angle from the interaction positions, the direction of the incident gamma ray source must be known a priori. This will be possible from the imaging capability of the 3-D CdZnTe detector.

In principle, three (or more) pixel events are also useful in polarization measurement and they provide more information. However, for energy as low as 300 keV, three or more pixel events in CdZnTe are rare. At higher energies, three or more pixel events should contribute more to the polarization measurement.

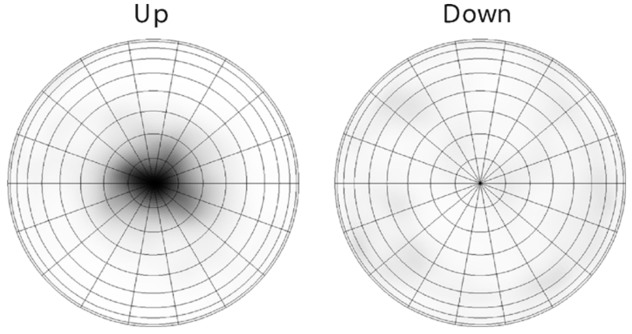

Fig. 8. Reconstructed image of the 90°-scattered photons after 24 iterations with list-mode maximum-likelihood algorithm. The image shows the up and down hemispheres of the 4π imaging space. Since the scintillator has a finite size, the reconstructed image is a distributed phantom.

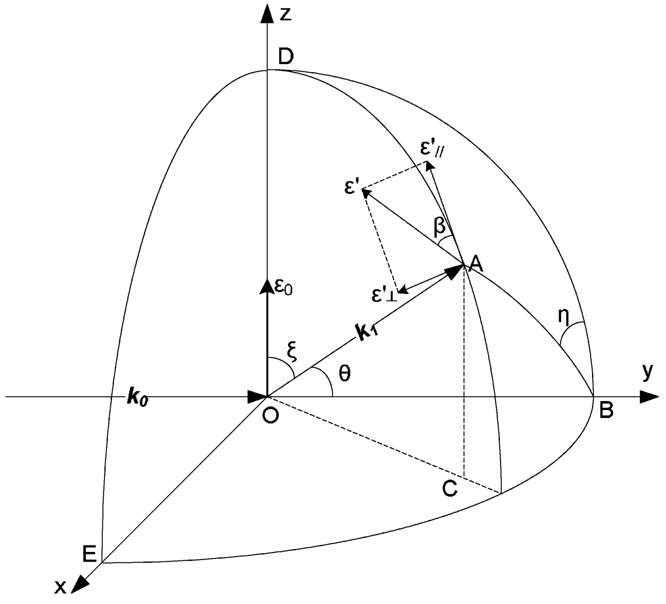

Fig. 9. Compton interaction at position O. ϵ_0 and ϵ' are the electric vectors of incident and scattered photons, respectively. θ is the scattering angle, ξ is the angle between the scattering direction and the electric vector of the incident photon, η is the angle between the electric vector of the incident photon and the scattering plane, and β is the angle between the electric vector of the scattered photon and OCAD plane.

V. CONCLUSION

A 3-D position sensitive CdZnTe detector has been demonstrated to be suitable for polarimetry. The measurement precision of polarization direction in this experiment was limited by the finite position resolution, the low gamma-ray energy and relatively small size of the detector. On a larger detector, especially at increased gamma-ray energies, the average separation between interactions will increase. This will improve the phase resolution. There are systematic errors in the polarization measurement caused by nonuniformity in the detection efficiencies of individual pixels, and the nonuniform efficiency at different scattering angles due to the square shape of the detector. Those systematic errors can be removed by rotating the detector during the observation. Although the Compton scattering cross section of CdZnTe is not higher than that of Si and Ge, the overall efficiency of a CdZnTe detector as a polarimeter is higher due to its higher photoelectric cross section. The 3-D position sensitivity enables the CdZnTe detector to do 4π imaging which can be utilized to determine the source direction and help the polarization measurement.

APPENDIX

This appendix calculates the theoretical amplitude of the modulation ratio for 90°-scattered photons of 662 keV gamma rays. The angles and directions involved can be visualized in Fig. 9.

The Klein-Nishina formula gives

$$d\sigma=\frac{r_0^2}{4}d\Omega\frac{k_1^2}{k_0^2}\left[\frac{k_0}{k_1}+\frac{k_1}{k_0}-2+4\cos^2\beta(1-\sin^2\theta\cos^2\eta)\right]. \tag{4}$$

For an unpolarized 662 keV gamma ray from the $^{137}\mathrm{Cs}$ source, the direction of its electric vector is uniformly distributed in 2π. Therefore, to calculate the polarization status of the 90°-scattered photon, η should be integrated over 2π. When the scattering angle θ equals $\pi/2$

$$\begin{aligned}\left.\frac{d\sigma_{\|}}{d\theta}\right|_{\theta=\frac{\pi}{2}}&=\frac{r_0^2}{4}\int_0^{2\pi}d\eta\frac{k_1^2}{k_0^2}\left[\frac{k_0}{k_1}+\frac{k_1}{k_0}-2+4(1-\cos^2\eta)\right]\\&=\frac{r_0^2}{4}\cdot\frac{2\pi k_1^2}{k_0^2}\left[\frac{k_0}{k_1}+\frac{k_1}{k_0}\right]\end{aligned} \tag{5}$$

$$\begin{aligned}\left.\frac{d\sigma_{\perp}}{d\theta}\right|_{\theta=\frac{\pi}{2}}&=\frac{r_0^2}{4}\int_0^{2\pi}d\eta\frac{k_1^2}{k_0^2}\left[\frac{k_0}{k_1}+\frac{k_1}{k_0}-2\right]\\&=\frac{r_0^2}{4}\cdot\frac{2\pi k_1^2}{k_0^2}\left[\frac{k_0}{k_1}+\frac{k_1}{k_0}-2\right].\end{aligned} \tag{6}$$

The above two equations are obtained from (4) with $\beta=0°$ for $\sigma_{\|}$ and $\beta=90°$ for $\sigma_{\perp}$. The ratio of k_1 and k_0 can be calculated from Compton scattering equation

$$k_1=\frac{k_0}{1+\alpha(1-\cos\theta)} \tag{7}$$

in which, $\alpha=h\nu_0/m_ec^2$ and $h\nu_0=662\ \mathrm{keV}$.

The polarization degree of the 90°-scattered photons is

$$\frac{\epsilon_{\|}^2-\epsilon_{\perp}^2}{\epsilon_{\|}^2+\epsilon_{\perp}^2}=\frac{2}{\frac{k_0}{k_1}+\frac{k_1}{k_0}+\frac{k_0}{k_1}+\frac{k_1}{k_0}-2}=0.577. \tag{8}$$

We first calculate the modulation ratio of linearly polarized photons at 288 keV, which is the scattered energy at 90° from 662 keV gammas. The modulation ratio of the actual 90°-scattered photon can be obtained by multiplying the modulation ratio of linearly polarized 288 keV photons by the actual polarization degree of incident gamma rays.

The scattering cross section of a linearly polarized 288 keV photon is

$$d\sigma=\frac{r_0^2}{4}d\Omega\frac{k_1^2}{k_0^2}\left[\frac{k_0}{k_1}+\frac{k_1}{k_0}-2\sin^2\theta\cos^2\eta\right]. \tag{9}$$

When we integrate over the scattering angle θ, we will get the cross section of a linearly polarized photon to be scattered into different azimuthal angles

$$d\sigma(\eta)=\frac{r_0^2}{4}d\eta\int_0^{\pi}\sin\theta d\theta\frac{k_1^2}{k_0^2}\left[\frac{k_0}{k_1}+\frac{k_1}{k_0}-2\sin^2\theta\cos^2\eta\right] \tag{10}$$

in which k_1/k_0 can be calculated from (7) with $h\nu_0=288\ \mathrm{keV}$, which is the energy of the 90°-scattered photon from a 662 keV gamma ray.

The modulation ratio of linearly polarized 288 keV photons calculated from (10) is 0.412.

Therefore, the theoretical modulation ratio expected in our experiment is $0.412\times0.577=0.238$.

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