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SPATIAL POLARIZATION DISTRIBUTION MEASUREMENTS OF GAMMA RAYS PRODUCED BY INVERSE COMPTON SCATTERING

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Abstract

Highly polarized MeV gamma rays produced via inverse Compton scattering (ICS) between a polarized laser and electron beam provide a unique probe for fundamental and applied physics. ICS gamma rays are characterized by energy tunability, quasi-monochromaticity, high polarization, and low divergence angle (<1 mrad), and are used for accelerator beam diagnostics, nuclear physics experiments, and evaluation of detectors for polarized gamma rays. A polarimeter that can measure the spatial polarization distribution of gamma rays is being developed at the UVSOR synchrotron facility. The measurement principle exploits the azimuthal asymmetry in Compton scattering cross-sections. Incident linearly polarized gamma rays interact with an iron target. Seven NaI detectors arranged in the scattering plane record the angular intensity distribution of scattered gamma rays. The determination of the polarization axis is achieved through systematic analysis of the azimuthal modulations. The spatial polarization distribution is measured by scanning a 1-mm diameter collimator in the beam cross-section in two dimensions. In this paper, we discuss the measurement results of the gamma-ray polarization axis relative to the laser polarization axis when the collimator position is along the central axis of the gamma-ray beam.

INTRODUCTION

Linearly polarized gamma rays are a special type of gamma rays in which the electromagnetic wave oscillates in a plane. Polarization measurements are essential in nuclear and astrophysics physics. In nuclear physics, polarized gamma-ray beams play an important role in investigating fundamental inquiries regarding nuclear structure and the properties of hadrons. Linearly polarized gamma-ray beams serve as a unique reference direction for studying photonuclear scattering and electromagnetic multipole transitions, including giant nuclear resonances [1,2]. Circularly polarized gamma rays, in conjunction with polarized targets, facilitate the investigation of nucleon spin structure through double-polarization techniques. They provide a precise and selective probe for exploring the spin polarizabilities of the nucleons [3,4]. In astrophysics, the polarization of gamma rays provides critical information about high-energy astrophysical phenomena such as black holes, neutron stars, and gamma-ray bursts, helping to explore the radiation mechanisms and the structure of the universe [5,6].

Polarized gamma ray can be generated by inverse Compton scattering (ICS) of a polarized laser by a relativistic electron beam. To perform various experiments using the polarization characteristics of gamma rays, it is important to understand the polarization characteristics of gamma rays generated by ICS and to measure them accurately. Matei et al. conducted polarization measurements of ICS gamma-ray beams via the d(gamma,n)p reaction under a collimator with a 19 mm-diameter aperture for beam definition at HIγS (High Intensity Gamma-ray Source) [7]. HIγS is also using an imaging system to measure the linear polarization of the gamma-ray beam during one cycle rotation [8]. Kamae et al. had used the multiple Compton method that uses a silicon detector stack to reconstruct Compton scattering of the gamma-ray energy degrading process to measure the polarization of gamma-rays [9]. Sun et al. had measured the asymmetry of the gamma-ray beam optical imaging system [10]. Zoglauer et al. determined the degree and angle of polarization using the tracking Medium Energy Gamma-ray Astronomy telescope MEGA [11]. Y. Taira et al. used the magnetic Compton scattering method to measure the circular polarization of ICS gamma rays [12]. In the UVSOR synchrotron facility, 6.6 MeV gamma rays can be generated by a 90-degree collisional ICS between a 750 MeV electron beam and an 800 nm laser. As the polarization characteristics of ICS gamma rays vary with the position of the beam cross section, understanding their spatial polarization distribution is important for gamma-ray applications, including the evaluation of astronomical gamma-ray detectors. However, detailed two-dimensional measurements of this distribution have not yet been conducted. To address this, a polarimeter based on asymmetry measurements of the Compton scattering cross section was developed at UVSOR, enabling precise measurement of the spatial polarization distribution of MeV polarized gamma rays.

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EXPERIMENTAL DETAILS

A schematic of the experiment is shown in Fig. 1. The ICS gamma-ray beam was collimated by a 1-mm diameter lead collimator with 180 mm length, positioned 7.3 m downstream from the collision point. A 100-mm-thick lead shield with a 20 mm × 20 mm square aperture aligned with the gamma-ray beam axis was positioned in front of the iron target to shield scattered radiation produced by the interaction between the ICS gamma rays and the lead collimator. An iron rod, 50 mm in length and 5 mm in diameter was used as the Compton scattering target. Seven NaI detectors were arranged behind the iron target at polar angle θ = 45° with azimuthal angles ϕ = 0°,30°, 60°, 90°, 120°, 150°,180°.

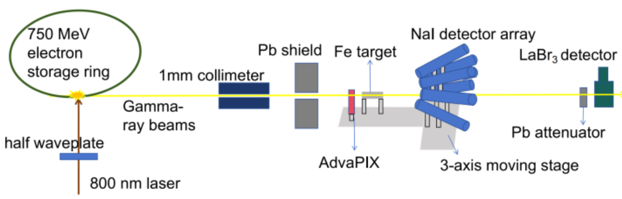

Figure 1: Schematic illustration of the polarization measurement of polarized gamma rays.

Figure 2 shows the spatial intensity distributions of linearly polarized gamma rays measured with a CdTe image sensor (AdvaPIX TPX3) with a pixel pitch of 55 μm × 55μm, an effective area of 14.08 mm× 14.08 mm, and a thickness of 1 mm. In this measurement, the CdTe sensor was placed upstream of the collimator. The distribution exhibits an expansion at 90° relative to the laser's polarization axis. Notably, a 90° rotation of the laser's polarization axis (from horizontal to vertical) induces a corresponding 90° rotation in the gamma-ray beam distribution. The intensity distribution exhibits a minimum at $\gamma\theta$=1 along the laser's polarization axis.

The energy spectrum of Compton scattered gamma ray measured by the NaI detector is presented in Fig. 3. Since only the signal output from the NaI detector synchronized with the laser is measured, the background due to bremsstrahlung is negligibly small. To systematically analyze the

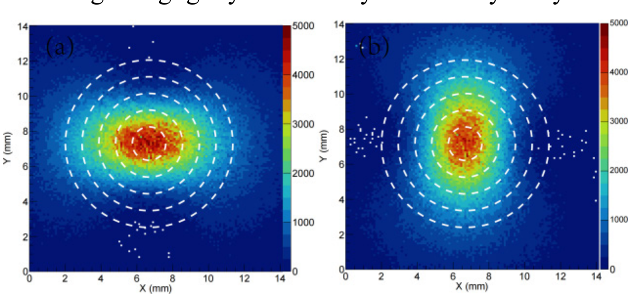

Figure 2: The spatial intensity distribution of ICS gamma rays generated by (a) vertically and (b) horizontally polarized lasers. The dotted concentric circles represent γ θ, corresponding to an increase from 0.2 to 1 in increments of 0.2.

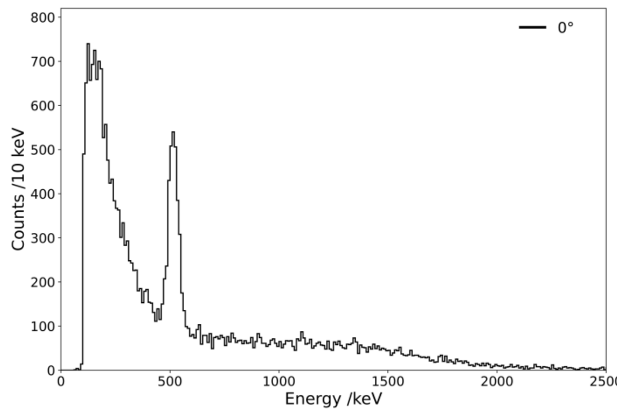

Figure 3: Energy spectrum of a NaI detector when collimator position is horizontal x = 0 mm and vertical y = 0 mm, corresponding to azimuthal angles ϕ=0°.

Compton scattering events, we selected an energy integration window of 0.6-2.0 MeV.

Figure 4 displays the azimuthal distribution of Compton-scattered gamma rays produced by vertically polarized incident gamma rays. The blue data points with error bars represent the counts measured by seven NaI detectors. Azimuthal modulation was clearly observed, with a maximum count at an angle of 90° relative to the gamma-ray polarization axis. The solid curve represents the theoretical fit based on the following equation, which describes the azimuthal dependence of the differential Compton scattering cross-section for polarized gamma rays [13].

$$\frac{d\sigma}{d\Omega} = \frac{r_0^2}{2}\frac{k^2}{k_0^2}\left\{\frac{k}{k_0} + \frac{k_0}{k} - 2sin^2\theta cos^2\phi\right\} \quad (1)$$

where σ is the cross section of Compton scattering, $r_0^2 = \frac{e^2}{4\pi\epsilon_0 m_e c^2} \approx 2.818 \times 10^{-15}$ m is the classical electron radius, k_0 and k_0 are the initial and final energies of the gamma rays, θ is the polar angle, and ϕ is the azimuthal angle relative to the laser polarization plane.

Figure 5 shows the polarization axis of ICS gamma-rays measured by systematically changing the angle of the half-wave(λ/2) plate. We confirmed that the polarization axis of the ICS gamma rays changes linearly with respect to the polarization axis of the laser.

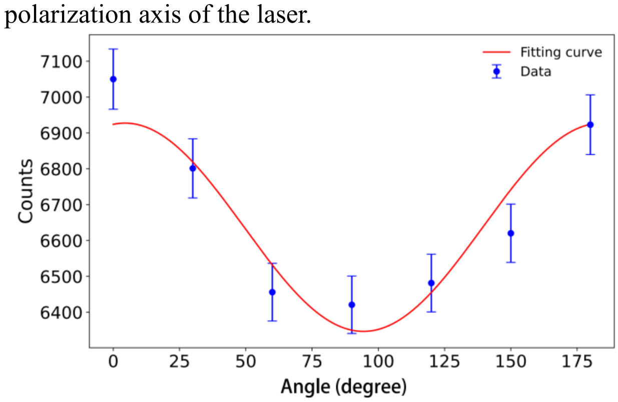

Figure 4: Azimuthal scattering distribution of vertically polarized gamma rays when collimator position is horizontal x = 0 mm and vertical y = 0 mm.

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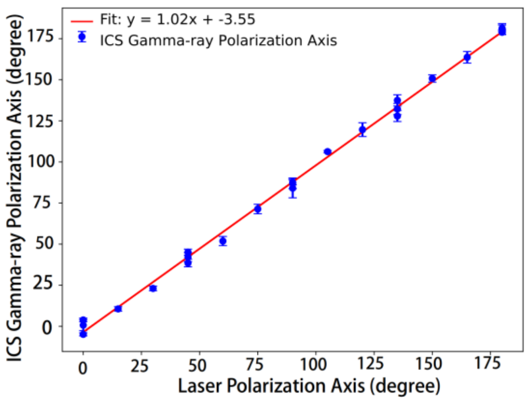

Figure 5: Change in the ICS gamma ray polarization axis as the laser polarization axis varied.

The two-dimensional spatial polarization distribution of ICS gamma rays can be obtained by performing similar measurements while moving the collimator, target, and NaI detector array in the two-dimensional plane perpendicular to the gamma-ray beam. By shifting the position of the lead collimator, the gamma-ray energy is changed in the range of 3 to 6.6 MeV. The similar asymmetric distribution shown in Figure 4 was obtained even if the gamma-ray energy is decreased.

CONCLUSION

A polarimeter that can measure the spatial polarization distribution of MeV ICS gamma rays has been developed at UVSOR. We show that the polarization axis of the gamma ray changes linearly with the rotation of the polarization axis of the laser. By scanning the distribution of ICS gamma beams in two dimensions using the developed polarimeter, we expect to be able to measure the change in the polarization axis of the gamma rays, which changes with the position of the beam cross-section. In the future, we will systematically measure the two-dimensional polarization distribution of gamma rays generated by linearly, circularly, and axially symmetric polarized lasers.

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