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Study of the polarimetric performance of a Si/CdTe semiconductor Compton camera for the *Hitomi* satellite

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ABSTRACT

Gamma-ray polarization offers a unique probe into the geometry of the γ-ray emission process in celestial objects. The Soft Gamma-ray Detector (SGD) onboard the X-ray observatory *Hitomi* is a Si/CdTe Compton camera and is expected to be an excellent polarimeter, as well as a highly sensitive spectrometer due to its good angular coverage and resolution for Compton scattering. A beam test of the final-prototype for the SGD Compton camera was conducted to demonstrate its polarimetric capability and to verify and calibrate the Monte Carlo simulation of the instrument. The modulation factor of the SGD prototype camera, evaluated for the inner and outer parts of the CdTe sensors as absorbers, was measured to be 0.649–0.701 (inner part) and 0.637–0.653 (outer part) at 122.2 keV and 0.610–0.651 (inner part) and 0.564–0.592 (outer part) at 194.5 keV at varying polarization angles with respect to the detector. This indicates that the relative systematic uncertainty of the modulation factor is as small as ~3%.

1. Introduction

Gamma-ray polarization provides a unique probe into the geometry of the γ-ray emission process in celestial objects, such as the geometries of accretion disks around stellar-mass black holes and the magnetic field structures of pulsar and pulsar wind nebula. Detection of γ-ray polarization from cosmological sources also provides a stringent test of the vacuum birefringence effect resulting from some quantum gravity models. For example, INTEGRAL/IBIS measurements reported a change in the polarization angle after the Crab flare indicating magnetic field reconnection [1]. IKAROS/GAPs and INTEGRAL/IBIS observations of γ-ray polarizations from γ-ray bursts (GRBs) have also placed the most stringent limits by far on the vacuum birefringence effect to date [2–4]. However, the INTEGRAL/IBIS measurements of the Crab polarization required observations of more than 10^6 s because IBIS was designed as a coded mask instrument and was not optimized as a Compton camera. The GAPS measurements of the GRB polarization were marginal because of insufficient statistics due to the limited scattering angle coverage and the poor angular resolution under the severe resource constraints. To advance studies of γ-ray polarization from celestial objects, γ-ray instruments with higher polarization sensitivities are required.

The Soft Gamma-ray Detector (SGD) onboard the *Hitomi* satellite, the sixth Japanese X-ray observatory launched on February 17, 2016 [5,6], is expected to provide 10 times better sensitivity in 60–600 keV than past and current observatories [7–10]. The SGD achieves high sensitivities by suppressing the background using a combination of the BGO active shield and a Compton camera. Internal backgrounds that

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cannot be rejected by the active shield can be suppressed by requiring consistency between the incident direction of the γ ray inferred by the Compton kinematics and the field of view defined by the collimator. The Compton camera consists of multiple layers of silicon (Si) sensors [11–13] surrounded by multiple layers of high-quality cadmium telluride (CdTe) sensors [14–16] to achieve good energy resolution and angular resolution for Compton kinematics. This design includes a compact camera with high detection efficiency enclosed in an active shield of a reasonable size that retains a sizable effective area.

The SGD also provides information on the polarization of the incident γ-rays because the Compton-scattering differential cross section depends on the azimuthal scattering angle with respect to the incident polarization vector. The SGD is also an excellent polarimeter because of its good angular resolution due to its highly segmented semiconductor sensors, and good scattering angle coverage [17,18]

To conduct reliable polarimetric measurements in orbit, a precise characterization of the Compton camera for polarized γ rays using a Monte Carlo (MC) simulation with a detailed model of the instrument is crucial. Therefore, we conducted a series of beam tests of prototypes for the SGD Compton camera using highly polarized ($\geq 99\%$) γ rays at the SPring-8[1] synchrotron radiation facility to demonstrate the polarimetric capability of the instrument, and to verify and calibrate the MC simulator. As reported by [18], we evaluated the polarimetric performance of an early prototype for the SGD Compton camera, and verified that the observed azimuthal scattering angle distribution agrees well with the MC simulation. In November 2015, we conducted a beam test using the final-prototype for the SGD Compton camera whose design is the same as that of the flight hardware.

In this study, we demonstrate the polarimetric capability of the SGD Compton camera and verify and calibrate the MC simulation based on the experimental data from the 2015 beam test. In Section 2, we briefly describe a method to derive polarization information using a Compton camera. A detailed description of the SGD Compton camera is given in Section 3. Section 4 describes the setup and procedures for the beam test at SPring-8. In Section 5, we provide the experimental results and comparisons with the simulations.

2. Method of polarimetric measurement

In this experiment, we adopted the standard method of polarimetric measurement for Compton polarimeters as described in Takeda et al. [18]. They derived the polarization information of the incident γ rays from a measured azimuth scattering angle (ϕ) distribution based on the dependence of the Compton-scattering differential cross section on the azimuthal scattering angle η with respect to the electric vector of the incident γ ray:

$$\frac{d\sigma}{d\Omega} = \frac{r_e^2}{2}\left(\frac{E'}{E_0}\right)^2\left(\frac{E'}{E_0} + \frac{E_0}{E'} - 2\sin^2\theta\cos^2\eta\right), \tag{1}$$

in which,

$$E' = \frac{E_0}{1 + (1 - \cos\theta)E_0/m_e c^2}, \tag{2}$$

where r_e is the classical electron radius, $m_e c^2$ is the electron rest mass, θ is a scattering polar angle, and E_0 and E' are the energies of the incident and the scattered γ rays respectively. Below we briefly describe the analysis procedure (see Takeda et al. [18] and references therein for details).

First, we measure the azimuthal angle distribution, $N_{\rm obs}(\phi)$, using the Si/CdTe Compton camera. Because the obtained distribution is affected by the detector response, $N_{\rm obs}(\phi)$ needs to be divided by the azimuthal angle distribution for nonpolarized γ rays, $N_{\rm iso}(\phi)$:

$$N_{\rm cor}(\phi) = \frac{N_{\rm obs}(\phi)}{N_{\rm iso}(\phi)/(\overline{N_{\rm iso}})}, \tag{3}$$

where $\overline{N_{\rm iso}}$ is the average per angle bin.

By referring to Eq. (1), we can see that the corrected azimuthal angle distribution follows a sinusoidal curve:

$$N_{\rm cor}(\phi) = A(1 + Q\cos 2(\phi - \phi_0 - \pi/2)), \tag{4}$$

where A is the normalization, Q is the so-called modulation factor, and ϕ_0 is the direction of the polarization vector with respect to the electric vector of the incident photon [19]. By fitting the experimental data with this model formula, we can derive the polarimetric parameters, i.e., ϕ_0 gives the polarization vector of the incident photon and Q is related to the polarization degree Π such that

$$\Pi = \frac{Q}{Q_{100}}, \tag{5}$$

where Q_{100} (i.e., the analyzing power) is the modulation factor for 100% linearly polarized γ rays. The accuracy of the analyzing power affects the sensitivity of the polarimetric measurement of the detector. In Section 5, we evaluate the accuracy of Q_{100} in the SGD Compton camera prototype via a comparison between the experimental data and the simulated data.

3. Compton camera of SGD

3.1. Design

Here we briefly summarize the design of the Compton camera (see [16] for details). The camera consists of top 32 layers of Si pixel sensors, bottom 8 layers, and 2 layers on each side of the CdTe pixel sensors, as shown in Fig. 1. The bottom and the side layers are composed of 2×2 and 2×3 CdTe sensors respectively. The Si and the CdTe sensors have 16×16 pixels and 8×8 pixels, respectively, with respective thicknesses of 0.6 and 0.75 mm. The pixel size is $3.2 \times 3.2\ \mathrm{mm}^2$ for both the Si and CdTe sensors. Fig. 2 displays the geometry of the camera with definitions of instrumental (camera) X-, Y-, and Z-axes.

Each set of 8×8 pixels is read by a single ASIC (VATA450.3) mounted on a Front-End Card (FEC). The front-end electronics of the Compton camera consists of four groups of 52 FECs, one ASIC Driver Board (ADB), and one ASIC Control Board (ACB). Eight or six ASICs are daisy chained for readout and control. The ASICs are controlled by an FPGA on the ACB. These components are packed into a $12 \times 12 \times 12\ \mathrm{cm}^3$ aluminum box. One of the daisy chained readouts did not work for the camera used in this experiment; therefore, one fourth of the pixels in the eight Si layers cannot detect γ rays. However, this is not the case for the flight-model SGDs.

3.2. Event reconstruction

When observing weak objects in orbit, we require that each SGD event involve Compton scattering in the detector to apply Compton kinematics. The simplest case is that the event interacts twice in the camera: once via Compton scattering in a Si sensor and once via photo-absorption in a CdTe sensor. The time width to identify coincidence hits is $\sim 10\ \mu\mathrm{s}$, and typical low energy thresholds for hits in a Si sensor and a CdTe sensor are ~ 5 and ~ 10 keV, respectively [16]. Once the locations and energies of the two interactions are measured, the Compton kinematics allows us to calculate the direction of the incident photon using the following formula:

$$\cos\theta = 1 + \frac{m_e c^2}{E_1 + E'} - \frac{m_e c^2}{E'}, \tag{6}$$

where E_1 and E' are the energy deposited in the Compton site and the photo-absorption site, respectively, and are related to the incident

[1] http://www.spring8.or.jp