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Performance study of Si/CdTe semiconductor Compton telescopes with Monte Carlo simulation

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Abstract

A Compton telescope with high angular resolution and high energy resolution is a promising detector for the next generation of astrophysics space missions aiming at hard X-rays and sub-MeV/MeV gamma-rays. We have been working on a semiconductor Compton camera based on silicon and cadmium telluride (Si/CdTe Compton telescope). The soft gamma-ray detector (SGD) employs a Si/CdTe Compton camera combined with a well-type active shield. It will be mounted on the NeXT mission, proposed to be launched around 2012. One Compton camera module in the SGD will consist of 24 layers of double-sided silicon strip detectors and four layers of CdTe pixel detectors. We carried out Monte Carlo simulations to investigate the basic performance of the detector. Design parameters of devices required in the simulation, such as energy resolution and position resolution of the detector, are based on the results from our prototype detector. From the simulation using current design parameters, the detection efficiency is found to be higher than 10% at $\sim$100 keV and the angular resolution to be 9° and 4.4° at 120 keV and 330 keV, respectively. The effects of changing the design parameters are also discussed.

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Keywords: Gamma-ray detector; Compton telescope; Monte Carlo simulation

1. Introduction

Gamma-rays in the energy range from several tens of keV to several MeV provide an important window to the study of energetic phenomena in the universe such as nucleosynthesis and particle acceleration. These phenomena are observed in objects such as pulsars, stellar black-hole candidates, supernova remnants, active galactic nuclei, and gamma-ray bursts. The observational sensitivity in this energy band, however, is relatively low due to high background levels, low detection efficiency, and limited angular resolution. Compton telescopes are promising detectors to overcome these problems since the direction of incident γ-rays is constrained by Compton kinematics, greatly reducing the background as compared with detectors which employ a coded mask or a collimator.

The first successful Compton telescope in orbit was COMPTEL aboard the Compton gamma-ray observatory (CGRO) [1]. COMPTEL observations provided pioneering results including all sky imaging from 1 to 30 MeV and spectroscopy of MeV gamma-ray lines [2]. But the number of detected objects was very small, with only 32 sources

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detected [3]. Thus improving the sensitivity is the key goal of the next generation detectors. This requires a higher detection efficiency, a lower instrumental background and better angular resolution [4]. A high density detector array with improved energy and position resolution is needed. With this point of view, Compton telescopes based on position-sensitive semiconductor detectors, such as Si, Ge, CZT, and CdTe, have been proposed and developed by various groups [5–10].

Our group has proposed building a Si/CdTe Compton telescope based on the recent achievements of the development of Si and CdTe semiconductor imaging detectors with high energy resolution [9]. A schematic drawing of a Si/CdTe Compton telescope is shown in Fig. 1. The telescope is based on a hybrid semiconductor gamma-ray detector consisting of layers of thin Si and CdTe to detect photons in a wide energy band (0.05–1 MeV). Through using a prototype Compton camera, we succeeded in reconstructing images and spectra of gamma-rays from 81 to 662 keV. We were also able to make photon polarization measurements [11–13].

The Si/CdTe Compton telescope is adopted as one of instruments on board the NeXT (New X-ray Telescope/Non-thermal Energy eXploration Telescope) mission, proposed in Japan as a successor to the current Suzaku X-ray mission. A detailed description of the instrument, refered to as the SGD (soft gamma-ray detector), is presented in Takahashi et al. [14]. Since the SGD must outperform previous soft γ-ray instruments in background rejection capability, the optimization of the design is of great importance. For this purpose, we have studied the performance of the Si/CdTe Compton telescope by using Monte Carlo simulations. Experimental results of the prototype Compton camera are used for assuming parameters of devices, for example, energy and position resolution of the detector. Initial results of simulations regarding the detection efficiency and performance as a polarimeter were presented in our previous publication [15]. In this paper, we present new results on the performance of the Si/CdTe detector in the SGD. In particular, the detection efficiency as a function of various design parameters and the angular resolution as a function of various data selection are described in detail.

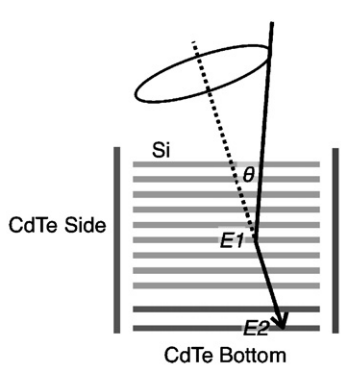

Fig. 1. Schematic picture of a Si/CdTe Compton camera. An incident photon is scattered at a silicon detector and then absorbed at a CdTe detector. E_1 and E_2 are energy deposited of the two hits, and θ is the scatter angle.

2. Simulation Setup

Fig. 2 shows a schematic diagram of the geometry of the detector used in the simulation. The telescope consists of 24 layers of double-sided silicon strip detectors (DSSDs) and four layers of thin CdTe pixellated detectors (CdTe Bottom) with a thickness of 0.5 mm. The sides are also surrounded by CdTe pixel detectors (CdTe Side). In order to lower the background dramatically and thus to improve the sensitivity, we combine a stack of Si strip detectors and CdTe pixel detectors to form a Compton telescope. This configuration is suitable for a Compton camera, since Si has a small cross-section for photo absorption even for very soft γ-rays (e.g. ~80 keV) and CdTe has a large cross-section for photo absorption due to their large atomic numbers ($Z_{\mathrm{Cd}} = 48$, $Z_{\mathrm{Te}} = 52$). The telescope is then mounted inside the bottom of a well-type active shield to further reduce the background by adopting a new concept, narrow-Field-of-View (FOV) Compton telescope [14,16].

The size of an individual DSSD is 50 mm × 50 mm with a thickness of 0.5 mm, and each DSSD has 125 strips on each side with a strip pitch of 0.4 mm. The energy

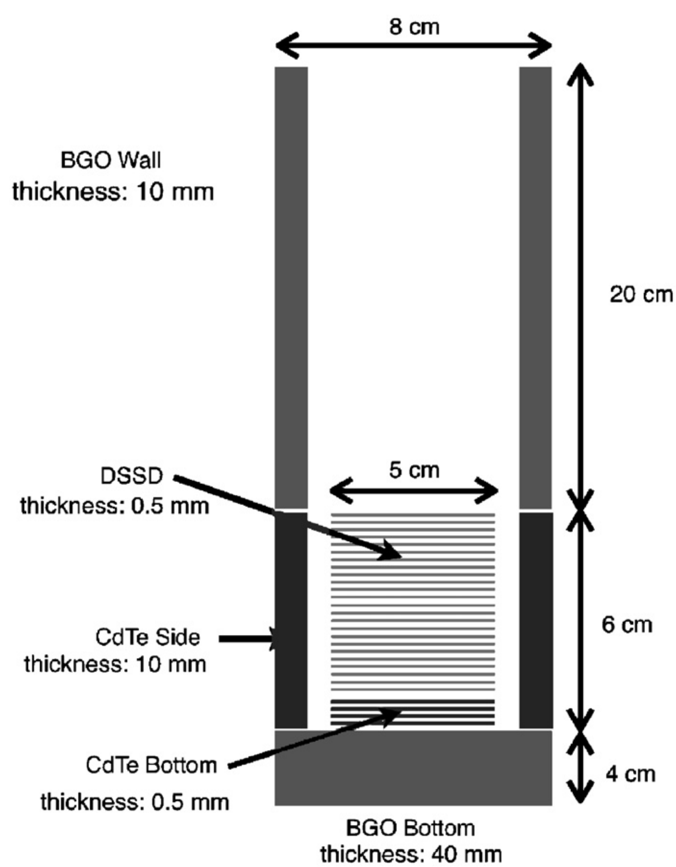

Fig. 2. The simulated geometry of the Si/CdTe Compton telescope.