SLAC-PUB-12556
June 2007

A Stacked CdTe Pixel Detector For a Compton Camera

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We are developing a semiconductor Compton telescope to explore the universe in the energy band from several ten keV to a few MeV. A detector material of combined Si strip and CdTe pixel is used to cover the energy range around 60 keV. For energies above several hundred keV, in constrast, the higher detection efficiency of CdTe semiconductor in comparison with Si is expected to play an important role as both an absorber and a scatterer. In order to demonstrate the spectral and imaging capability of a CdTe-based Compton camera, we developed a Compton telescope consisting of a stack of CdTe pixel detectors as a small scale prototype. With this prototype, we succeeded in reconstructing images and spectra by solving the Compton kinematics within the energy band from 122 keV to 662 keV. The energy resolution (FWHM) of reconstructed spectra is 7.3 keV at 511 keV. The angular resolution obtained at 511 keV is measured to be 12.2°(FWHM).

1. Introduction

The hard X-ray and gamma-ray bands ranging from several ten keV to a few MeV are important windows for exploring the high energy phenomena such as nucleosynthesis and particle acceleration in the universe. However, observation sensitivity in this energy band has been still limited, due to high background, low detection efficiency, and difficulty of imaging by means of focusing technology. A semiconductor Compton telescope utilizing the good energy and position resolution of semiconductors is one of the most promising approaches to realize a breakthrough in this energy band.

Based on our recent achievements for high resolution CdTe and Si imaging detectors (1; 2; 3; 4; 5), we have proposed a new Si/CdTe semiconductor Compton telescope as a next generation Compton telescope (6; 7). The basic concept of the Si/CdTe Compton camera is to utilize Si as a scatterer and CdTe as an absorber. Si works as a good scatterer with energies above 60 keV due to large Compton scattering efficiency, and CdTe has high photo absorption efficiency as an absorber due to the large atomic numbers of Cd ($Z = 48$) and Te ($Z = 52$). According to the measurements with a prototype composed of six layers of Double-sided Si strip detector (DSSD) and CdTe pixel detectors, we successfully achieved Compton reconstructed images of gamma-rays from 81 keV to 662 keV. An angular for 511 keV gamma-rays were measure to be resolution of 3.9 ° (8; 9; 10).

In order to achieve much higher efficiency for gamma-rays above a few hundred keV, a CdTe detector with a thickness of several mm is required. However, a monolithic detector with such a thickness is difficult to operate due to the small mobility life time product. One idea to achieve such a thick device is a stacked thin CdTe detector (11; 12; 13). The merit of adopting a stacked thin detector is that we can take advantage of high energy resolution throughout the energy range from several ten keV to a few hundred keV. At energies above 300 keV, the stacked CdTe detector by itself works as a Compton telescope. To understand the behavior of the stacked CdTe detector, we developed a prototype.

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Submitted to Nucl.Instrum.Meth.

Work supported in part by US Department of Energy contract DE-AC02-76SF00515

2. A Prototype Stacked CdTe Pixel Detector

We have constructed the prototype detector composed only of four CdTe pixel detectors. Fig. 1 shows the arrangement of the detectors. Three CdTe pixel detectors are stacked with an interval of 12 mm, and one detector are placed at the side of them in order to obtain events with large Compton scattering angles. Each detector can work as both a scatter and an absorber. The entire detector system was kept at a temperature of −20 ˚C, and the bias voltage for the all detectors was set to 700 V.

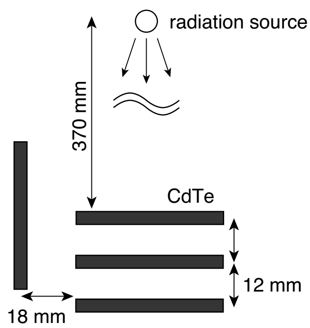

Figure 1. Configuration of the prototype stacked CdTe pixel detector. Each detector works as both a scatter and an absorber.

The 8 × 8 CdTe pixel detector used in the prototype is based on the Schottky CdTe diode device, utilizing indium as the anode and platinum as the cathode. The CdTe crystal is manufactured by ACRORAD in Japan, which features very low leakage current and high uniformity (1; 11; 14). Fig. 2 shows the photo of the detector. The detector has dimensions of 18.55 mm × 18.55 mm and a thickness of 500 μm. The platinum side is divided into 8 by 8 pixels surrounded by a guard ring electrode with a width of 1 mm. The pixel size is 2 mm × 2 mm, and the gap between each pixel is 50 μm. Each pixel is connected to a fanout board by bump bonding technology developed in cooperation with Mitsubishi Heavy Industry in Japan (15). The signal lines are directly connected to the input of readout electronics, a low noise analog LSI VA32TA (5).

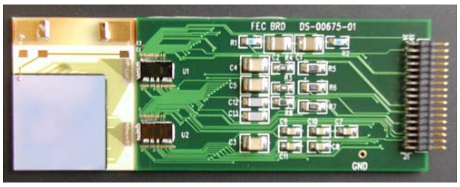

Figure 2. A photo of a 8 × 8 CdTe pixel detector.

Fig. 3 shows spectra of ^{22}Na and ^{57}Co with one of the CdTe pixel detectors employed in the prototype stacked CdTe pixel detector. The energy resolution (FWHM) is 5.0 keV and 1.6 keV for the gamma-rays of 511 keV and 122 keV, respectively. The energy threshold is measured to be as low as 7 keV.

3. Prototype Performance

For Compton reconstruction, we selected two-hit events, one hit in a CdTe detector and one hit in another CdTe detector. Here, one hit means that only one channel has a pulse height above 14 keV. As described in the reference (16), the Compton scattering angle is calculated from the information of deposited energies and positions by the Compton kinematics. Compton cones are drawn in the sky, event by event using the scattering angle and the hit positions.

Fig. 4 shows the image obtained with a ^{22}Na gamma-ray source. A circle with a radius of 10 ˚ is shown together as a reference. It should be noted that the images are symmetric due to the arrangement of the CdTe pixel detectors being symmetric except for the one at a side.

Background rejection using a Compton image is an important feature for a Compton telescope.

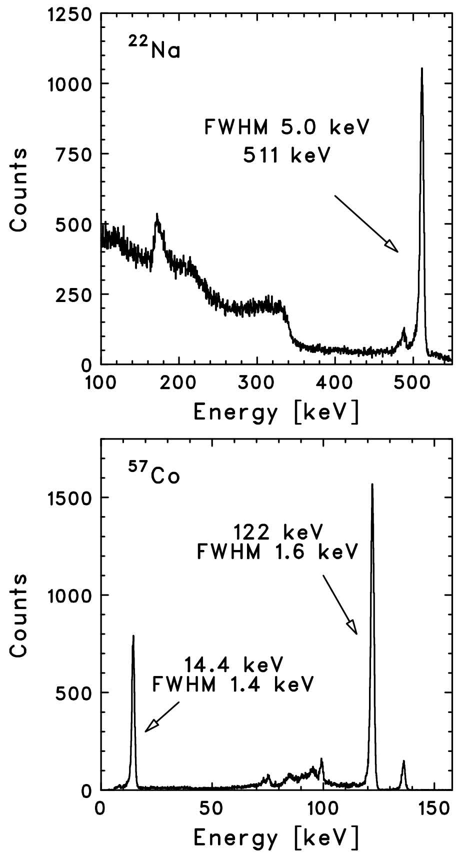

Figure 3. ^{22}Na and ^{57}Co spectra obtained with a 8 × 8 CdTe pixel detector. The detector is operated at a temperature of −20 °C, with a bias voltage of 1200 V. Each spectrum is drawn by summing all 64 channels.

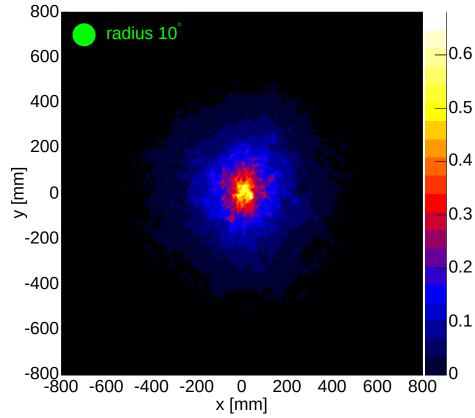

Figure 4. Compton reconstructed image of 511 keV. The images was drawn by using the energies from 500 keV to 520 keV.

The dotted lines in Fig. 5 shows the spectrum obtained by simply summing the deposited energies for all two-hit events. The spectrum is composed of a 511 keV gamma-ray line and a large number of scattering components. On the other hand, the solid line spectrum in Fig. 5 is made from the events which coincide with the direction of the source position. As shown in the figure, the scattering components are reduced by a factor of 0.16, while the 511 keV peak retains 61 % of its counts. The energy resolution (FWHM) is 7.3 keV for 511 keV gamma-rays.

In order to evaluate the angular resolution ($\Delta\theta$) of our prototype Compton telescope, we compared the calculated scattering angles (θ_{comp}) with those defined by the location of gamma-ray source and hit positions (θ_{geom}) (see the reference (9)). We investigated the distribution of the angular resolution (FWHM) for the gamma-rays of ^{57}Co, ^{133}Ba, ^{22}Na, and ^{137}Cs. As plotted in Fig. 6, the angular resolution becomes better as the incident gamma-ray energy become higher. The obtained angular resolution is 35.9 $^{\circ}$ at 122 keV, and 12.2 $^{\circ}$ at 511 keV, respectively. The values are significantly larger that those of the Si/CdTe

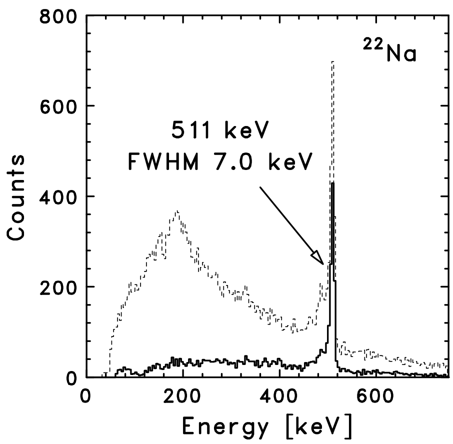

Figure 5. Compton reconstructed spectra of ^{22}Na. A dotted line show all two-hit events, while a solid line shows the events corresponding to the source direction within 15 $^{\circ}$.

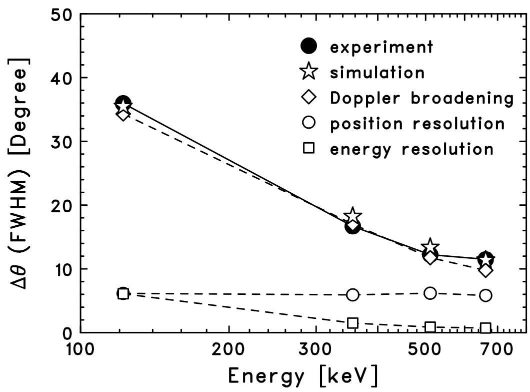

Figure 6. Relation between incident gamma-ray energy and angular resolution (FWHM). The simulation stands for the sum of the three contribution.

Compton Camera.

In Fig. 6, we also plotted the estimated contribution of the position resolution, the energy resolution, and the Doppler broadening effect. The calculation method is describe in our paper (9). The angular resolution is almost limited by the effect of Doppler broadening, which becomes smaller as the incident energy becomes higher.

4. Conclusions

A Si/CdTe semiconductor Compton telescope is a promising detector for future gamma-ray missions in the energy band from several tens of keV to a few MeV. In order to demonstrate higher efficiency in higher energy band, we verified a concept of a stacked CdTe pixel detector, which acts as both a scatterer and an absorber. With the prototype detector, we succeeded in reconstructing Compton images and spectra for gamma-rays from 122 keV to 662 keV. The energy resolution (FWHM) of reconstructed spectra is 7.3 keV at 511 keV. The high energy resolution is due to the high performance of thin CdTe pixel detectors. The obtained angular resolution is 35.9 $^{\circ}$ at 122 keV, and 12.2 $^{\circ}$ at 511 keV, which is mainly dominated by the effect of Doppler broadening.

The prototype stacked CdTe pixel detector shows higher efficiency in terms of reconstructed spectra than that of the prototype Si/CdTe Compton telescope (10), while the angular resolution of the former is worse than that of the latter. However, the angular resolution becomes a degree scale, when the gamma-ray energy goes up to a few MeV. Once the stacked CdTe pixel detector is combined with Si layers, the detector will give us a good performance from several 10 keV up to several MeV.

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