PROCEEDINGS OF SCIENCE

PoS(ICRC2023)902

Development of an electron-tracking Compton camera using SOI pixel sensor for sub-MeV gamma-ray observations

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We have been developing an electron-tracking Compton camera (ETCC) using an SOI pixel semiconductor detector for observation sub-MeV gamma rays. An ETCC can reconstruct arrival directions of gamma rays each event as a point using the recoil directions of electron tracks, therefore, this camera does not increase false spot comparing with a conventional Compton camera. Also, an ETCC can discriminate between the gamma rays and backgrounds by detecting the track length and energy of recoil electrons. ETCC using a semiconductor detector is useful for detecting line gamma rays because of its high-energy resolution. To detect recoiled electron tracks, we focused on an SOI pixel semiconductor detector XRPIX2b, which was developed by Kyoto University. The sensor has a small pixel pitch of 30 μm and a trigger circuit mounted on each pixel, therefore we can select only candidate gamma-ray events and read out only the selected pixels. We developed a prototype electron-tracking Compton camera using XRPIX2b sensor. We evaluated the detection capability of recoil electron due to 511 keV gamma rays. From the results of the evaluation in the laboratory, we succeeded in detecting recoil-electron tracks and estimating the recoil directions using the track image. Furthermore, we confirmed to be able to detect the radioisotope position using back-projection method. We obtained sufficient quantitative detailed performance data of the current sensor to develop a novel sensor for ETCC.

38th International Cosmic Ray Conference (ICRC2023)
26 July - 3 August, 2023
Nagoya, Japan

1. Sub-MeV gamma-ray observations

The observation of sub-MeV gamma rays is an important probe to elucidate various high-energy phenomena in astrophysics. For example, radioisotopes such as ^{56}Ni emits 847-keV gamma-ray emission [1, 2]. Furthermore, positrons are released via nucleosynthesis due to supernova explosions. These positrons collide with electrons and produce 511-keV gamma rays. We can elucidate a mechanism of nucleousynthesis due to a supernova explosion by observing the types of line gamma rays and these amounts. Several gamma-ray detectors including the INTEGRAL/SPI, have preciously observed 511-keV and sub-MeV gamma-ray lines from the galactic plane [3]. Various candidate phenomena have been proposed to produce the positrons from which the 511-keV gamma-ray originate [4], but the origins have not yet been identified. To elucidate these high-energy phenomena, a high-sensitivity observation by the background reduction is essential for the sub-MeV gamma-ray observation.

Using an advanced Compton camera with semiconductor detectors is suitable to observe sub-MeV line gamma rays because it can exclude continuum gamma-ray background and particle background owing to its good energy resolution. Moreover, it can estimate an arrival direction of a gamma-ray event by event by detecting recoil electron tracks. For detecting the complicated recoil directions of electrons, a small-pitch pixel sensor is required. Herein, we focused on fine pixel-pitch (a few ten μm) semiconductor detectors using the silicon-on-insulator (SOI) technique [5]. An SOI pixel sensor is a monolithic semiconductor detector, which has a small pixel pitch (a few tens μm), wide-band energy detection, a high tolerance for radiation damage, and low-power requirements. Furthermore, the sensor has a good time resolution (a few μs) compared with the CCD sensor. A good time resolution is essential for a Compton camera to detect coincidence events.

In a previous study, an advanced Compton camera using an SOI pixel sensor was developed for nuclear medicine diagnostics [6]. They demonstrated its ability to detect recoil-electron tracks produced by gamma rays with energies ranging from a few hundred keV to 1 MeV. As a result of this finding, we anticipate using an advanced Compton camera with an SOI pixel sensor for astrophysical sub-MeV gamma-ray studies In this study, we developed a prototype Compton camera and quantitatively investigated the detection capability of the pixel sensor for the sub-MeV astrophysical observation.

2. Electron tracking Compton camera

A Compton camera is a technique for visualizing that is used to specify the gamma-ray arrival directions. Such a camera is suitable for sub-MeV gamma-ray observations because Compton scattering dominates these energies. A Compton camera typically comprises a scatterer and an absorber which are both position sensitive detectors (Fig. 1). The scatterer detects the interaction position, energy, and the absorber detects the interaction position and energy of the scattered gamma ray. The scattering angle calculated by Compton kinematics θ_k is as follows:

$$\cos\theta_k = 1 - \frac{m_e c^2}{E_2} - \frac{m_e c^2}{E_1 + E_2}, \tag{1}$$

where E_1, E_2, m_e, c denote energy of the recoiled electron in the scatterer, energy of the scattered gamma-ray photon in the absorber, electron mass, speed of light, respectively. In particular, the quantities E_1 and E_2 correspond to the kinematic energy of the recoiled electron E_e and the energy of the scattered gamma-ray photon E'_γ, if the event includes only one Compton scattering event and one photoabsorption event. For a conventinal Compton camera, an incident direction of a gamma ray is estimated by a ring shape. Then, we obtain the position of a gamma-ray source by accumulating the multiple rings. This type of Compton camera produces false spots in a reconstructed image, because the back-projection method estimates the probability distribution of the location of a radiation source as a smeared ring shape (Fig. 1 left). Conversely, an ETCC reduce the false spots by detecting the electron tracks. An ETCC can detect the direction of the incident gamma-ray as a point for event by event by using the recoil direction of an electron at a scatterer (Fig. 1 right). The arrival direction $\vec{s}_{\rm rcs}$ of the incident gamma-ray is calculated as follows:

$$\vec{s}_{\rm rcs} = \frac{E_2}{E_1 + E_2}\vec{g} + \frac{\sqrt{E_1(E_1 + 2m_{\rm e}c^2)}}{E_1 + E_2}\vec{e}, \tag{2}$$

where $\vec{g}$, and $\vec{e}$ denote the unit vector of the scattered gamma-ray, and unit vector of the recoiled electron, respectively.

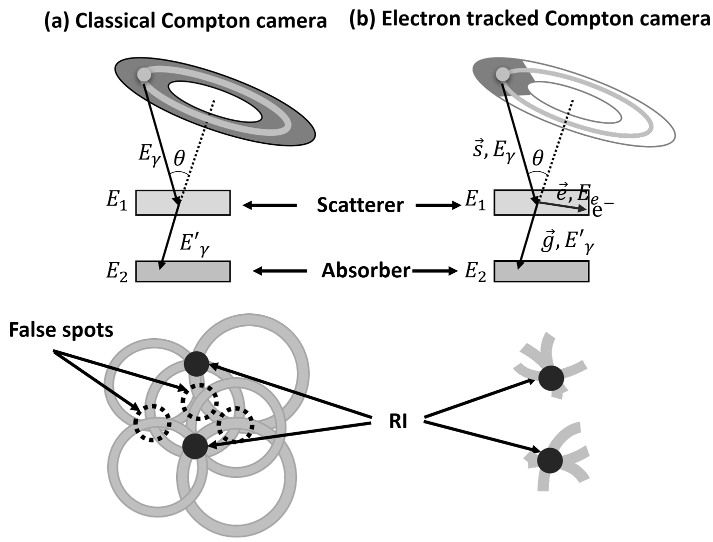

Figure 1: Principle of a conventional Compton camera (left) and an electron-tracking Compton camera (right). A reconstructed image measured by a conventional Compton camera has false spots. An advanced Compton camera can reduce the false spots by detecting recoil-electron tracks.

3. Development of prototype ETCC

We adopted an SOI pixel sensor as the scatterer. SOIPIX is a semiconductor pixel sensor using a wafer with a high-speed and low-power large-scale integration circuit with SOI complementary metal-oxide semiconductor (CMOS) technology [7]. Among SOIPIX sensors, we used on the XRPIX2b developed for X-ray astronomy by Kyoto University [8], [9]. XRPIX2b consists of 152 ×152 pixels on a 300 μm thick wafer, and its pixel size is 30 μm × 30 μm. Furthermore, this sensor can obtain only signal events by mounting a trigger circuit at each pixel. The signals are readout and digitized by an SOI evaluation board with SiTCP (SEABAS) [10]. As a basic performance, the energy resolution at 13.9 keV was 1.8 keV (FWHM).

As an absorber, a CsI (Tl) scintillation detector was adopted for the prototype because we need a high detection efficiency to obtain significant statistics of coincidence events in the laboratory experiments. The scintillation detector consists of a CsI (Tl) cube 3.5 cm on a side and a photomultiplier tube (PMT). The PMT is H11432-100 manufactured by Hamamatsu Photonics K. K. The output signal is amplified by a non-inverting amplifier AD8009 manufactured by Analog Device. We used a 16-channel flash ADC board with the SiTCP technology manufactured by Bee Beans Technologies Co., Ltd., which was developed by the KEK Open-It project [10]. The energy resolution of this detector was 22 keV at 511 keV (FWHM).

4. Evaluation of the detection capability of the prototype Compton camera

We investigated the detection capability of a sensor using the prototype Compton camera. We employed 511-keV gamma rays as typical energy in the sub-MeV energy bands. The directions θ, ϕ, and ψ were defined as the scattering angle, rotation angle, and inclination angle of the recoil-electron track, respectively (Fig. 2).

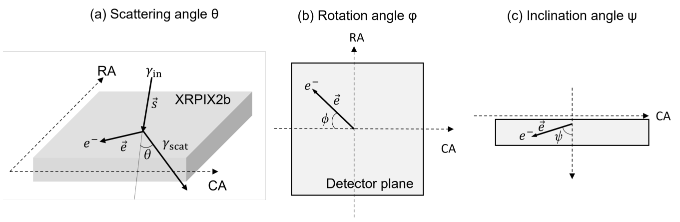

Figure 2: Definition of angles of recoil-electron tracks; angles θ, ϕ, and ψ denote (a) scattering angle of the incident gamma-ray, (b) rotation angle of the recoil-electron in detector plane, and (c) inclination angle of recoil-electron in Si sensor.

Fig. 3 shows the arrangement of the detectors and a radiation source. We used ^{22}Na radioisotope (511 keV) and the temperature was −20°C. In this evaluation, we estimated a recoil direction using the reconstructed images of electron tracks while changing various conditions for running electrons, such as scattering angles (θ), rotation angles (ϕ), and inclination angle (ψ). The effective time was 5 h and the actual measurement time was approximately 20 h. Also, we compared the results obtained the tests with the results of Monte Carlo simulation using Geant4 simulator [11].

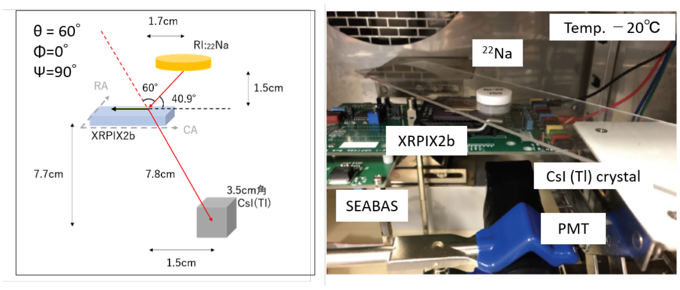

Figure 3: Arrangement of the detectors.

We explain the analysis method as an example when the scattering angle is 90°. We selected coincidence events as follows: first, we set the energy threshold of the scatterer at 3 keV, which corresponds to approximately 10 σ, here, σ is the standard deviation of the distribution of the electrical noise. For absorber, the energy threshold was 20 σ. Next, we selected coincidental events using the timing data of the scatterer and absorber. We selected events within the time difference range of ±400 ns. Then, we selected recoil-electron events using track images obtained from scatterer. To distinguish a track image from defective pixels, we defined a track to consist of more than two adjacent pixels. Finally, we used energy constraint $E_\gamma = E_1 + E_2$. We estimated the deposited energy to be 256 keV when the scattering angle of the incident gamma ray was θ = 90°. In this test, we selected events for which the absorbed energy was within the range of 256±40 keV and the total energy was within 511±40 keV. We determined the range of ±40 keV based on the energy resolution of the absorber. After the event selections, we obtained the track images due to Compton scattering, presented in Fig. 4. We succeeded in detecting recoil-electron tracks and confirmed that the track images are similar to those expected from Geant4 simulation.

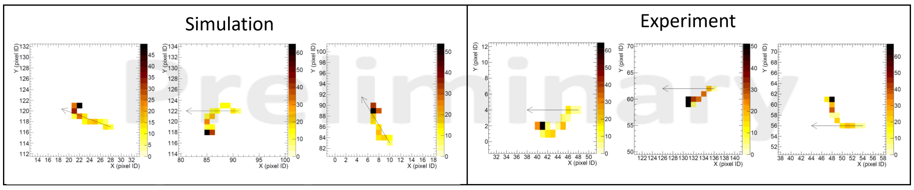

Figure 4: Comparisons of the recoil-electron tracks obtained from the simulations (left) and from the experiments (right) when 511-keV gamma rays are incident on the sensor at θ = 90°, ϕ = 0°, and ψ= 90°. The color bar indicates the deposited energy (keV). The arrows show the estimated recoil directions of the electrons on the detection plane.

Using the track image, we estimated the recoil direction. We defined a Bragg peak as the pixel with the highest energy in the track. After that, we searched the pixels detected signal and the interaction position was defined as the farthest hit pixel from Bragg peak. We calculated the recoil direction toward the energy centroid of adjacent pixels around the interaction position. Then, we selected events using a constraint of the recoil angle α, which is the angle between the directions of the scattered gamma ray and the recoil direction of the electron tracks. The two vectors $\vec{g}$ and $\vec{e}$ define the angle $\alpha_{\rm geo}$

$$\cos\alpha_{\rm geo} = \vec{g}\cdot\vec{e}, \tag{3}$$

and $\alpha_{\rm kin}$ indicates the angle calculated from Compton kinematics, stated as follows:

$$\cos\alpha_{\rm kin} = \left(1 - \frac{m_{\rm e}c^2}{E_2}\right)\sqrt{\frac{E_1}{E_1 + 2m_{\rm e}c^2}}. \tag{4}$$

Thus, the scattering direction can be identified by selecting an event with small values of $\Delta\alpha = \alpha_{\rm kin} - \alpha_{\rm geo}$. Fig. 5 shows the distributions estimated recoil directions when the scattering angles were changed. The solid line and dotted line indicate the recoil direction obtained from the experiments and simulations, respectively. From this result, we succeeded to estimate the recoil direction using the track image.

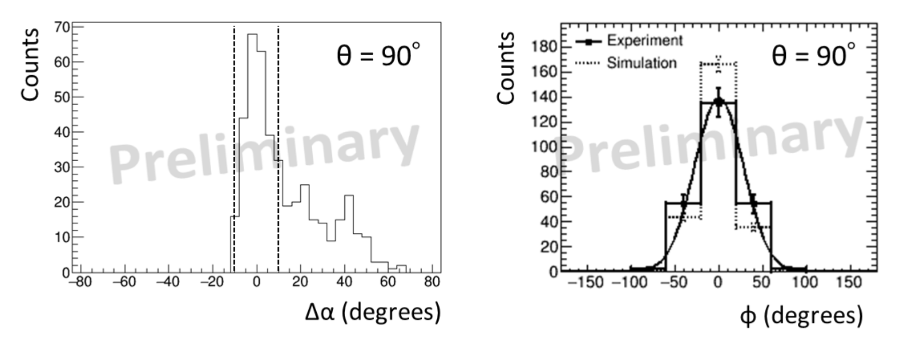

Figure 5: Distribution of $\Delta\alpha$ (left). In this measurement, the scattering, rotation, and inclination angles were 90°, 0°, and 90°, respectively; we selected events within $\Delta\alpha \pm 10°$. The right figure is distribution of estimated recoil direction. The solid line and dotted line indicate the recoil direction obtained from the experiments and simulations, respectively.

We reconstructed the gamma-ray image using the obtained data. This data was θ=90°, ϕ=0°, and ψ = 90°. The radiation source was placed at (63.5°, 0°) in the experiment. The arrival directions were calculated by Compton kinematics using Eq. 2. We projected the calculated gamma-ray source position on the screen. We compared the conventional Compton camera and an advanced Compton camera as presented in Fig. 6. For a conventional Compton camera, the location of a radiation source was estimated only as a smeared ring shape in this test. Conversely, an advanced Compton camera can estimate the arrival direction of gamma-ray each event. The reconstructed image exhibited a point source at (61.2±0.4°, −0.5±0.3°), obtained by fitting the distribution of the in tensity with 2-dimensional Gaussian function. Thus, we succeeded to obtain the location of a radiation source.

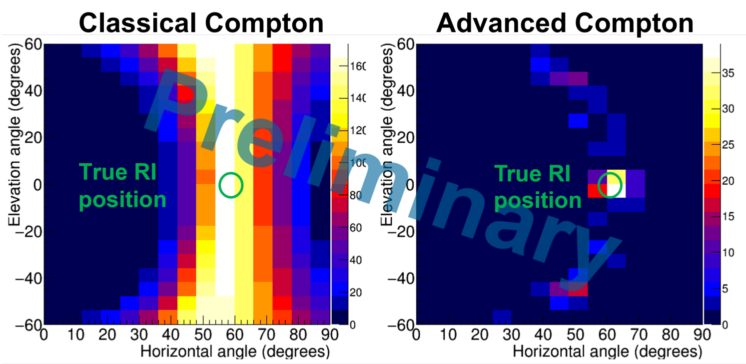

Figure 6: Comparisons of the reconstructed images using a classical Compton reconstruction method and an advanced Compton reconstruction method.

5. Conclusion

We developed a prototype advanced Compton camera for sub-MeV gamma-ray observation. We adopted an Kyoto University's XRPIX2b sensor for detecting the recoil electron tracks of gamma rays caused by Compton scattering. We succeeded to detect recoil-electron tracks created by Compton scattering of 511-keV gamma rays using the experiments and simulations. Furthermore, we demonstrated that we can estimate the recoil direction using images of electron tracks. Also, we succeeded to detected a location of a radiation source using back-projection reconstruction method as an advanced Compton camera. For future plans, we need to evaluate the detection capability and the detail performance of Compton camera quantitatively. After evaluation of the current SOI pixel sensor, we will develop an optimal sensor to adopt an advanced Compton camera for sub-MeV astrophysical observations.

6. Acknowledgment

This work was supported JSPS KAKENHI Grant-in-Aid for Young Scientists Number 17K14264, 19K14743 and the Sasakawa Scientific Research Grant 2019-2025 from the Japan Science Society. This work was partially carried out by the joint research program of the Institute for Cosmic Ray Research, the University of Tokyo. We would like to thank the Open source consortium of instrumentation (Open-It), Japan, SOI quantum imaging sensor consortium, and Enago (www.enago.jp) for its English language review.

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