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DEVELOPMENT OF GAMMA-RAY IMAGING DETECTOR BASED ON MICRO-TPC

T. Nagayoshi[1], **T. Tanimori**[1], **H. Kubo**[1], **R. Orito**[1], **M. Ueno**[1], **A. Ochi**[2], **Y. Nishi**[3], **S. Koishi**[4]

[1]*Department of Physics, Kyoto University, Kitashirakawa-oiwake-cho, Sakyo-ku, Kyoto, 602-8502, Japan*
[2]*Department of Physics, Kobe University, 1-1 Rokkodai-cho, Kobe-shi, Hyogo, 657-8501, Japan*
[3]*The Institute of Physical and Chemical Research (RIKEN), 2-1 Hirosawa, Wako-shi, Saitama, 351-0198, Japan*
[4]*Department of Physics, Tokyo Institute of Technology, 2-12-1 O-okayama, Meguro-ku, Tokyo, 152-8551, Japan*

Abstract

A new gamma-ray imaging detector has been proposed. This consists of the Micro TPC for recoil electron tracking and scintillator as a scattered gamma-ray detector. Basis of the Micro TPC is a new micro-pattern gas detector named "Micro Pixel Chamber (μ-PIC)". We have developed the large area (10cm $\times$ 10cm) μ-PIC and performance tests are now on progress. Expected performances of this new gamma-ray detector were estimated by computer simulation using EGS4. A new gamma-ray reconstruction algorithm was established and tested using output from EGS4. In principle, incident gamma ray was completely reconstructed with precision of 1 degree.

1 Introduction

High energy photon imaging detector is important device for astronomy, diagnoses, etc. Today, many type of detectors for low energy X-ray (<10keV) and high energy gamma ray (>100MeV) have been developed. However imaging technique of intermediate region gamma ray around 1 MeV have not established yet. In the case of a collimator-based detector, scattered gamma rays due to Compton scatterings in collimator become serious background source. One solution for MeV gamma-ray imaging was double Compton method, which use typically two solid state position-sensitive detectors such as scintillator or semiconductor. For this type, available information for gamma-ray reconstruction is positions and energy deposits by Compton scatterings occurred in the both detectors. A track of a Compton recoil electron in solid state detector is so short that it is observed as a point. Therefore the recoil direction of the electron cannot be used for gamma-ray reconstruction. A candidate determined by one pair of events forms an "*event circle*". At least three event pairs are necessary to determine an incident direction uniquely. If recoil direction of electron were measured, incident direction of gamma ray would be completely determined from only one event. Our new gamma-ray detector enables us to observe electron track by a Time

Projection Chamber (TPC) as well as scattered gamma ray detected by a solid state detector. True gamma-ray imaging will be realized by this detector.

Main source of MeV gamma ray is transition emission due to decay of radioactive nuclei. For example, in high energy astrophysics, MeV gamma ray can be used as a probe to investigate the process of nucleosynthesis. In nuclear medicine, MeV gamma-ray imaging is a very useful diagnostic tool. Our new gamma-ray imaging detector will be a promising device in those fields.

2 Micro TPC

Compton scattering is dominant interaction for MeV region gamma ray. For the purpose of gamma-ray imaging using Compton scattering, it is necessary to measure directions and energies of both scattering gamma ray and recoil electron due to the interaction. However it is difficult to obtain recoil direction of electrons. Because electron tracks are easily deflected by multiple scattering in material. Thus straight track available for gamma-ray reconstruction is very short.

Fine tracking detector is needed to observe short electron tracks. Very good position and timing resolution is required for the detector. Micro pattern gas detector such as MicroStrip Gas Chamber (MSGC) [1] is the most suitable device. We have been developed two-dimensional MSGC as a real-time X-ray imaging detector [2]. Our MSGC also works as a TPC for three-dimensional tracking with accuracy of 100 μm [3].

Energy of typical Compton recoil electron is about 1MeV, which is similar to the electron mass. Energy deposit of a particle is minimum in this energy region; this particle is called minimum ionizing particle (MIP). Enough high gas gain ($\gtrsim 10^4$) is required to detect tracks of MIPs. For MSGCs, probability of discharge cannot be negligible in such high gain operation. In short, both stable and high gain operation is difficult for MSGCs.

To solve this problem, we developed the new micro pattern gas detector, which was named "Micro Pixel Chamber (μ-PIC)". Schematic structure of the μ-PIC is shown in Fig. 1. This detector is manufactured based on double sided printed circuit board (PCB) technology. Cathode strips with holes of 210μm are printed on one side of the 100μm thick substrate. On the other side of the substrate, anode strips are printed orthogonally to the cathode electrodes. Pixel electrodes of 50μm diameter are formed at the center of cathode holes, and they are connected to the anode strips. This technology is easily extend for the production of the larger area detectors up to a few meters in principle. We have developed a test board of μ-PIC having 3cm $\times$ 3cm detection area, high gas gain ($> 10^3$) and stability were simultaneously achieved [4, 5]. Recently, a μ-PIC having large detection area (10cm $\times$ 10cm) have been developed. Figure 2 is the microscopic photograph of the new μ-PIC. Performance test of the large area μ-PIC is now on progress.

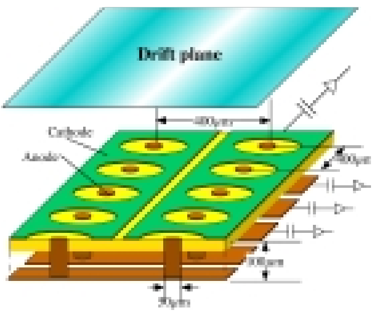

Figure 1: Schematic illustration of the μ-PIC.

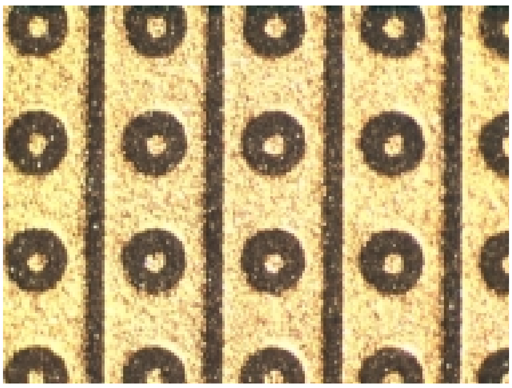

Figure 2: Close up view of detection area of the μ-PIC.

3 Detection Principle

The new gamma-ray imager consists of the Micro TPC based on μ-PIC and scintillation detector with photomultiplier tube (PMT) array. The schematic structure is shown in Fig. 3. In order to suppress diffusion of electron tracks, the drift volume is divided into two regions. Detection electrodes of the μ-PIC are set on both bottoms of each drift volume. When a Compton scattering occurred in the gas chamber, a scattered gamma ray is absorbed in the scintillator around the gas chamber. Position, energy, and timing information are obtained from the scintillator. A three-dimensional track of the recoil electron is reconstructed by the Micro TPCs. Timing information from the scintillator is used as a trigger for electron tracking. If recoil electrons are observed, new information — recoil direction — is available for gamma-ray reconstruction. It was impossible for conventional detectors based on double Compton method.

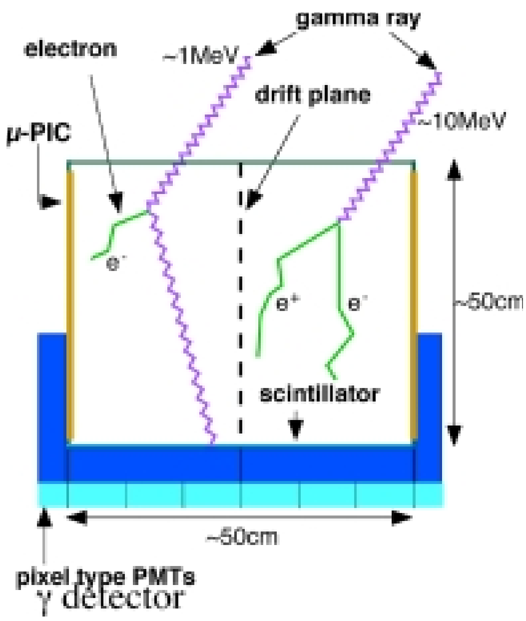

Figure 3: Schematic structure of the gamma-ray detector based on Micro TPC

When a gamma-ray photon is scattered by an angle θ_{sc} due to Compton effect, following equation (Compton formula) holds for the scattering angle and energy of scattered gamma ray $E_{\gamma'}$;

$$\cos\theta_{sc} = 1 - \frac{m_e c^2}{E_{\gamma'}} + \frac{m_e c^2}{E_{\gamma'} + E_k}, \tag{1}$$

where m_e, c, and E_k are rest mass of an electron, light velocity, and kinetic energy of a recoil energy, respectively. In this process, all momenta of incident gamma ray, scattered gamma ray, and recoil electron lie on the same plane, which we call this "*interaction plane*". When direction vectors of a scattered gamma ray and a recoil electron are obtained, an interaction plane is uniquely determined by those vectors. Candidates of incident gamma-ray direction vectors are restricted to two intersections of the interaction plane and the candidate cone determined by the Compton formula. The one true direction vector of an incident gamma ray is selected from these two candidates by another geometrical condition which the true direction vector must lie between the scattered gamma-ray vector and the recoil electron vector. This method requires only one Compton event to reconstruct one incident gamma ray. This is great advantage which former double Compton detectors did not have.

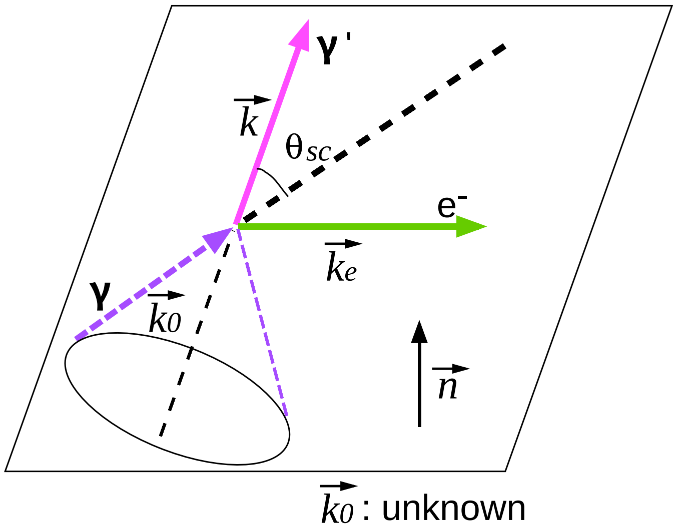

Figure 4: Illustration of gamma-ray reconstruction using Compton scattering. $\vec{k_0}$, $\vec{k}$, and $\vec{k_e}$ are direction vector of incident gamma ray, scattered gamma ray, and recoil electron, respectively. Here $\vec{k_0}$ is unknown vector. And $\vec{n}$ is normal vector of the interaction plane. θ_{sc} describes scattering angle of gamma ray.

4 Simulation Study

Performances of the Micro TPC gamma-ray detector were estimated by computer simulation using EGS4. The EGS4 is a very convenient program package for Monte-Carlo simulation of high energy electrons and photons [6].

The geometry for calculation is a cubic shape, of which inside pure xenon gas is filled with an atmospheric pressure. Volume of the gas chamber is 50cm $\times$ 50cm $\times$ 50cm. Also 2 cm thick GSO crystal covers the gas chamber like Fig 3.

4.1 Behavior of gamma ray and electron in gas

When both a recoil electron and a scattered gamma ray are observed in the gas volume and in the scintillator respectively, it is regarded as an effective event. The detection efficiency is about 1 % for 1 MeV gamma ray [7]. In this energy region, Efficiency variation is almost negligible for the incident angle of between 0 degree (vertical) and 40 degrees. Where the incident angle is greater than 40 degrees, the efficiency is obviously decrease (see Fig. 5). This means that the estimated field of view (opening angle) is about 90 degrees.

While electrons passing through gas the volume, the tracks are quite bent by multiple scattering. The deflection of electron tracks affects the accuracy of reconstructed gamma-ray direction. Here the deflection angle of electron track is defined as angular deviation from the initial direction of the recoil electron at the point on the track passing through the 3 mm distance. The deflection at 3 mm flight is less than 1 degree for 1 MeV incident gamma rays [7]. As the result, very accurate tracking is expected for this gamma rays.

In the case of Compton scattering of low energy gamma ray, Doppler broadening of scattered photon energy have to be taken into account. For this purpose, the LSCAT is included in the EGS4 code. The LSCAT is low energy photon expansion for EGS4 code [8]. Figure 6 shows energy distribution of gamma rays scattered to 45 degrees. In this simulation, energy of incident gamma ray is fixed on 500 keV. Certainly, the Doppler broadening is seen with FWHM of about 1%. This

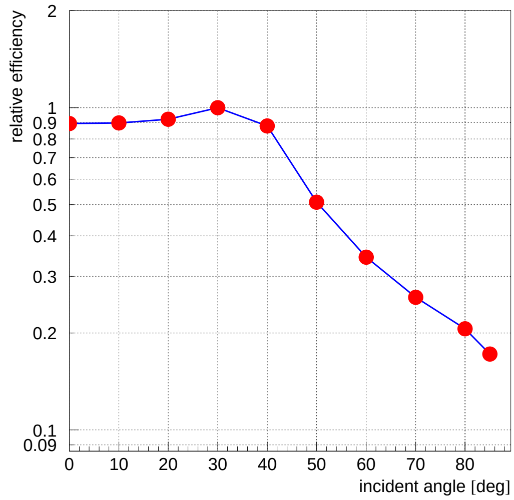

Figure 5: Variation of detection efficiency as a function of incident angle.

broadening is smaller than the energy resolution of scintillator as scattered gamma-ray detector. Therefore, Doppler broadening of scattered gamma ray will be negligible.

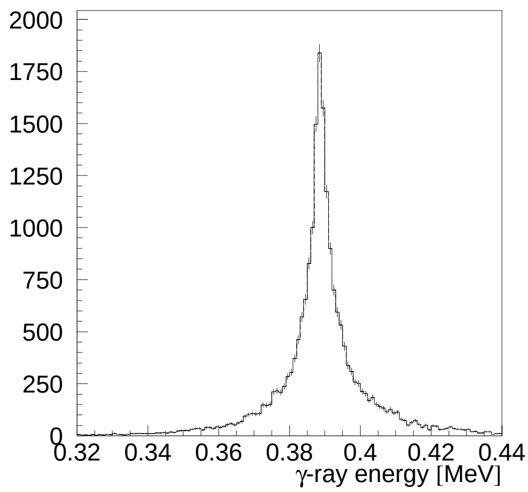

Figure 6: Energy distribution of gamma rays scattered to 45 degrees

4.2 Scintillation photons

Position sensitive scintillators are used for detection of scattered gamma rays. Dispersion of scintillation light in crystal is an important property to determine absorption points of scattered gamma rays.

The geometry of scintillator is a 2 cm thick slab of GSO single crystal. In simulation, the bottom surface is divided into 7×7 square-shaped segments. Length of a side of each segment is

0.5 or 1 inch. It was assumed that a photomultiplier tube (PMT) was sticked on the bottom of each segment. When a gamma ray interact in GSO crystal, scintillation light is isotropically emitted, and then detected by PMTs. The incident position of gamma ray is reconstructed by photon distribution obtained by each PMT. For simplicity, following conditions are assumed; (1)incident gamma ray is perpendicular to the surface of the crystal, (2)incident position is a point on the center cell of the crystal, (3)attenuation of scintillation light in crystal is ignored, (4)quantum efficiency of each PMT is 20 %.

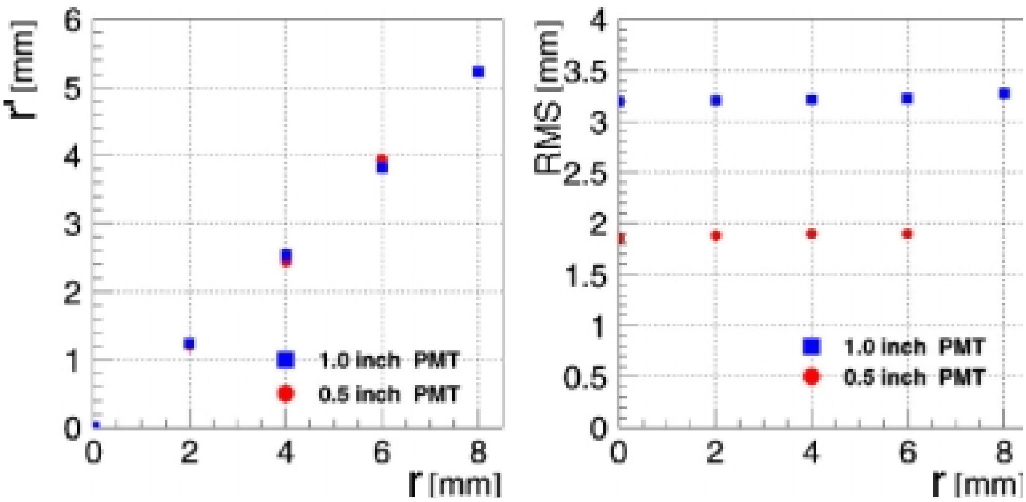

Figure 7: Relation between apparent incident position r' and true incident position r (left), and variation of position resolution (rms) as a function of true incident position r (right). Energy of incident gamma ray is 0.7 MeV for all cases.

Figure 7 shows the result of this simulation. Although reconstructed incident position, which is named "apparent position", is shifted toward the center of the segment (Fig. 7 left), this shift is proportional to the true incident position and independent on PMT size. This means that the apparent position can be corrected using the proportional relation. On the other hand, position resolution of PMT is almost independent on incident position. The obtained position resolution is about 2 mm (rms) for 0.5 inch PMTs (see Fig. 7 right).

4.3 Gamma-ray reconstruction

We have established a gamma-ray reconstruction algorithm using pairs of Compton recoil electrons and scattered photons. It was combined with EGS4 code and worked as a subroutine of EGS4. Output from EGS4 are position of a Compton event, energy deposit and absorption position of a scattered gamma ray, and energy deposit and terminal point of straight track of a recoil electron. They are fed by the reconstruction program, and incident gamma ray is reconstructed using the method mentioned in section 3. If a Compton scattering occurred in the scintillator and the scattered gamma ray escaped from the detector, whole energy is not deposited in the scintillator. In this case, cosine of scattering angle θ_{sc} calculated by equation (1) is apt to inconsistent. Thus these events are rejected in the reconstruction program.

The result of this calculation is shown in Fig. 8. Energy of incident gamma ray is 1 MeV. Polar and azimuth component of the incident direction are also fixed at 30 degrees and 60 degrees, respectively. Since the purpose of this simulation is to examine the reconstruction method, approximately ideal resolution of position and energy is assumed. As the result, very fine angular resolution of $\sim$ 2 degrees (FWHM) was obtained.

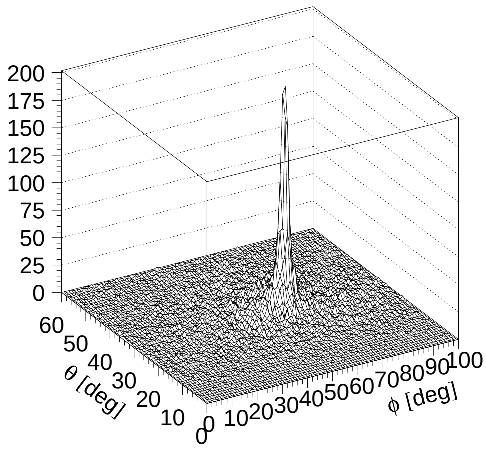

Figure 8: Distribution of reconstructed gamma rays

5 Summary

We propose the new gamma-ray imaging detector which consists of the micro TPC as Compton recoil electron tracker and scintillator as an Anger camera for scattered gamma rays. The micro TPC is based on a new micro pattern gas detector "Micro Pixel Chamber (μ-PIC)". μ-PIC with large detection area have been developed, and operation test is now on progress.

Performances of the gamma-ray detector are estimated by EGS4. For 1 MeV gamma rays, detection efficiency of 1 % was obtained. The field of view is expected to be 90 degrees in opening angle. We simulated Doppler broadening of scattered gamma rays by LSCAT combined to EGS4. It turned out that effect of Doppler broadening is negligible. Behavior of scintillator is also simulated. Obtained position resolution is 2 mm for 0.5 inch PMTs, which is independent on incident position.

Finally, the gamma-ray reconstruction algorithm is tested using output from EGS4. As the result, incident gamma rays are completely reconstructed by each Compton event. Angular resolution of 2 degrees can be achieved, in principle.

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