[2] H. Kubo, et al., Nucl. Instr. and Meth. A 413 (2003) 94;
K. Miuchi, et al., Nucl. Instr. and Meth. A 535 (2004) 236.

[3] R. Orito, et al., Nucl. Instr. and Meth. A 513 (2003) 408;
A. Takada, et al., Nucl. Instr. and Meth. A 546 (2005) 258.

[4] A. Bressan, et al., Nucl. Instr. and Meth. A 424 (1999) 321.

[5] K. Terasawa, et al, in: Proceedings of the 19th Workshop on Radiation Detectors and their Uses, KEK Proceedings, vol. 2005-12, 2005, p. 63.

[6] J.A. Simpson, Ann. Rev. Nucl. Part. Sci. 33 (1983) 330.

[7] The MIT LNS Drift Gases R&D Experiment, (http://cyclo.mit.edu/drift/www/).

[8] R. Orito, et al., IEEE Trans. Nucl. Sci. 51 (2004) 1337.

[9] T. Nagayoshi, in: Proceedings of the 20th Workshop on Radiation Detectors and Their Uses, KEK Proceedings, vol. 2006-7, 2006, p. 1.

[10] J.F. Ziegler, J.P. Biersack, U. Littmark, SRIM-The Stopping and Range of Ions in Matter, Pergamon, New York, 1985.

[11] T. Doke, et al., Radiat. Meas. 33 (2001) 373.

資料 19

資料(20)

Development of Electron Tracking Compton Camera using micro pixel gas chamber for medical imaging

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Abstract

We have developed the Electron Tracking Compton Camera (ETCC) with reconstructing the 3-D tracks of the scattered electron in Compton process for both sub-MeV and MeV gamma rays. By measuring both the directions and energies of not only the recoil gamma ray but also the scattered electron, the direction of the incident gamma ray is determined for each individual photon. Furthermore, a residual measured angle between the recoil electron and scattered gamma ray is quite powerful for the kinematical background rejection. For the 3-D tracking of the electrons, the Micro Time Projection Chamber (μ-TPC) was developed using a new type of the micro pattern gas detector. The ETCC consists of this μ-TPC ($10 \times 10 \times 8\,cm^3$) and the $6 \times 6 \times 13\,mm^3$ GSO crystal pixel arrays with a flat panel photo-multiplier surrounding the μ-TPC for detecting recoil gamma rays. The ETCC provided the angular resolution of 6.6° (FWHM) at 364 keV of ^{131}I. A mobile ETCC for medical imaging, which is fabricated in a 1 m cubic box, has been operated since October 2005. Here, we present the imaging results for the line sources and the phantom of human thyroid gland using 364 keV gamma rays of ^{131}I.
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1. Introduction

We have realized both full ray tracing and the background rejection for MeV and sub-MeV gamma ray imaging by detecting the direction of the scatted electron in Compton process [1–3]. Although the track of the scattered electron was proposed to be useful for higher energy (>2 MeV) gamma ray in the Compton camera based on silicon strip detectors [4–8], multiple scatterings in dense matter intrinsically prevent from obtaining a sufficient angular resolution of it in those energy regions. Hence, a gas-tracking device looks a unique useful detector

to catch such a fine track. By measuring both the directions and energies of a recoil gamma ray and a recoil electron in the gas detector as shown in Figs. 1a, the direction of the incident gamma ray can be definitely determined for each Compton scattering. Furthermore, a residual measured angle between the scattered electron and the recoil gamma ray (hereafter, we say α angle) is used for the kinematical background-rejection. This α angle is also calculated from the measured hit positions and energy deposits, and used for the kinematical constraint. Thus, a full ray-tracing method surely provides gamma-ray images of higher quality with less radiation dose. As well known, the detection efficiency of the gas detector is low, but it provides both a large detection volume and an easy handling of signals due to the high gain of it. A simulation

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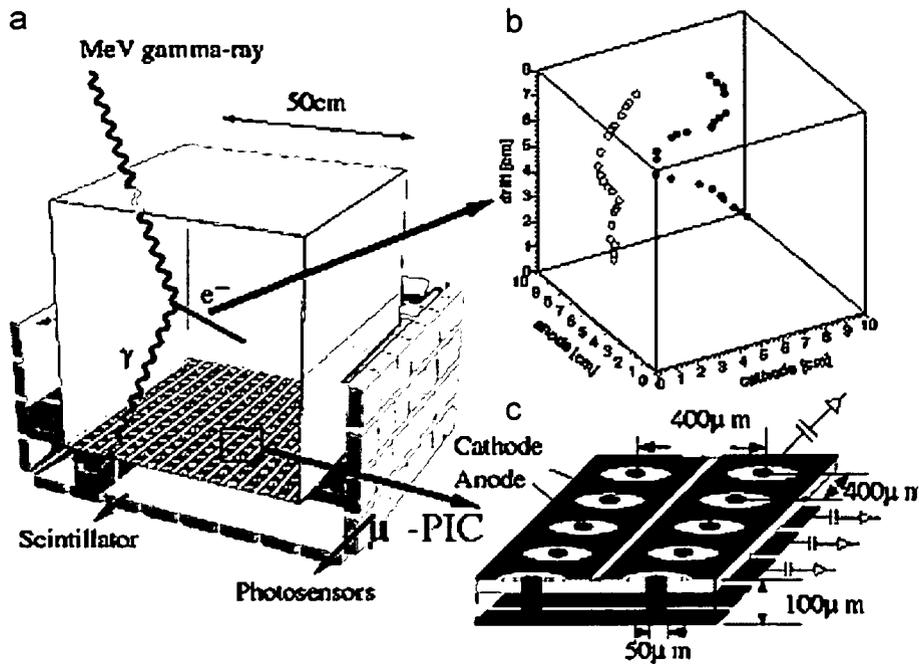*E-mail address:* tanimori@cr.scphys.kyoto-u.ac.jp (T. Tanimori).

Fig. 1. (a) Conceptual structure of Electron Tracking Compton Camera (ETCC). (b) Typical tracks of electrons from β-decay detected by the μ-TPC. (c) Schematic structure of μ-PIC.
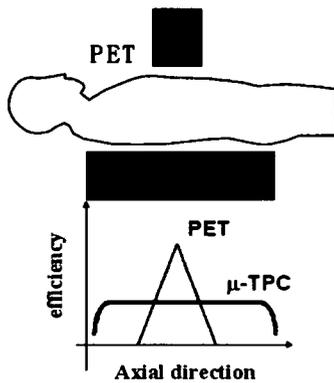

Fig. 2. Schematic comparison of the efficiencies of PET and ETCC along the axial direction of a human body.

study indicates that a 30 × 30 × 30 cm³ gas detector with Xe or CF₄ gas pressured by several times atmosphere provides the detection efficiency of a few percent for 500 keV gamma rays, which is better than the typical efficiency of SPECT. Also, such a large volume detector gives a flat efficiency and position resolution as shown in Fig. 2. On the other hand, those of Positron Emission Tomography (PET) are quite good at the center, but linearly worse from the center. Compton camera generally have a wide field of view of 2–4 sr, which covers a large area by ~4 times of the detector size. For the 30 × 30 cm² gas detector, its detection area covers the whole body. Thus, a large-area ETCC will surely provide us to new benefits even for the use of radio pharmaceutical which are now used for SPECT and PET.

2. Instrument and imaging performance

In order to realize such an ETCC, we developed the Micro Time Projection Chamber (μ-TPC) for the 3-D tracking of the recoil electrons [1–3]. Typical reconstructed tracks of the low-energy electrons in Compton scattering are shown in Fig. 1b. The μ-TPC consists of a new type of the gaseous proportional two-dimensional wireless position-sensitive detector, or a Micro Pixel Gas Chamber (μ-PIC) [9,10] as shown in Fig. 1c, and a drift volume. The prototype camera consisted of the 10 × 10 × 8 cm³ μ-TPC with an argon–ethane gas mixture (9:1) and the Anger camera with a large 30 × 30 × 1.5 cm³ NaI(Tl) single scintillator and a 6 × 6 2-in. photo-multiplier array for detecting the scattered gamma rays [11]. For this prototype, the angular resolutions of 12° and 34° (FWHM) for Angular Resolution Measure (AMP) and Scatter Plane Deviation (SPD) were obtained for 662 keV gamma rays when the energy of the incident gamma ray was used as a known parameter [11]. In 2005, we improved this detector as follows; the uses of GEM developed by Sauli et al. [12] as an intermediate electron multiplier above the μ-PIC and 6 × 6 × 13 mm³ GSO crystal pixel arrays with a flat panel photo-multiplier surrounding the base and side of the μ-TPC instead of the Anger camera [13–15]. By these improvements, we achieved a stable operation of the μ-TPC with a high gain of >20,000 (μ-PIC:2000, GEM:10) during 1 year, and obtained the energy resolution of the μ-TPC with ~20% at 22.2 keV. In addition, good energy and position resolutions of GSO scintillation array were obtained to be ~3 mm and 9% at 662 keV (FWHM), respectively. Then, combined energy resolution of the
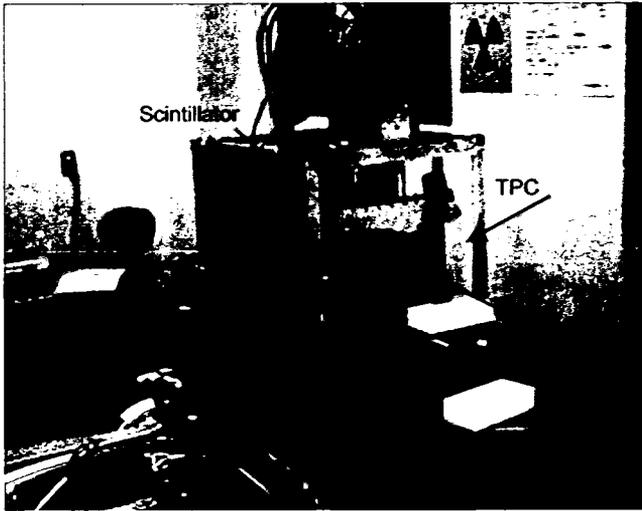
Fig. 3. Photograph of the mobile ETCC. All detectors, electronics, and computers are installed in the wagon.

ETCC for gamma rays was obtained 15% at 662 keV (FWHM). Using this improved ETCC, we obtained an ARM resolution of ~7° at 662 keV (FWHM) with measuring the total energy of the incident gamma ray, of which details are reported in Ref. [15]. Based on this improved ETCC, we have developed a mobile Compton camera fabricated within a 1 m cubic box as shown in Fig. 3 [15]. The angular resolutions of ARM and SPD at 364 keV gamma rays of ^{131}I were improved from 12° and 100° to 6.6° and 77° due to the improvement of the electron reconstruction. We have measured simultaneously the images of the two different energy gamma-ray sources ([133]Ba: 356 keV and [137]Cs: 662 keV) as shown in Fig. 4, where two images are obviously distinguished by the energy spectrum. This is a unique ability expected mainly for the Compton camera in medical use. In Ref. [15], similar images using the point sources of [137]Cs: 662 keV and [133]Mn: 853 keV were already presented. In this time,
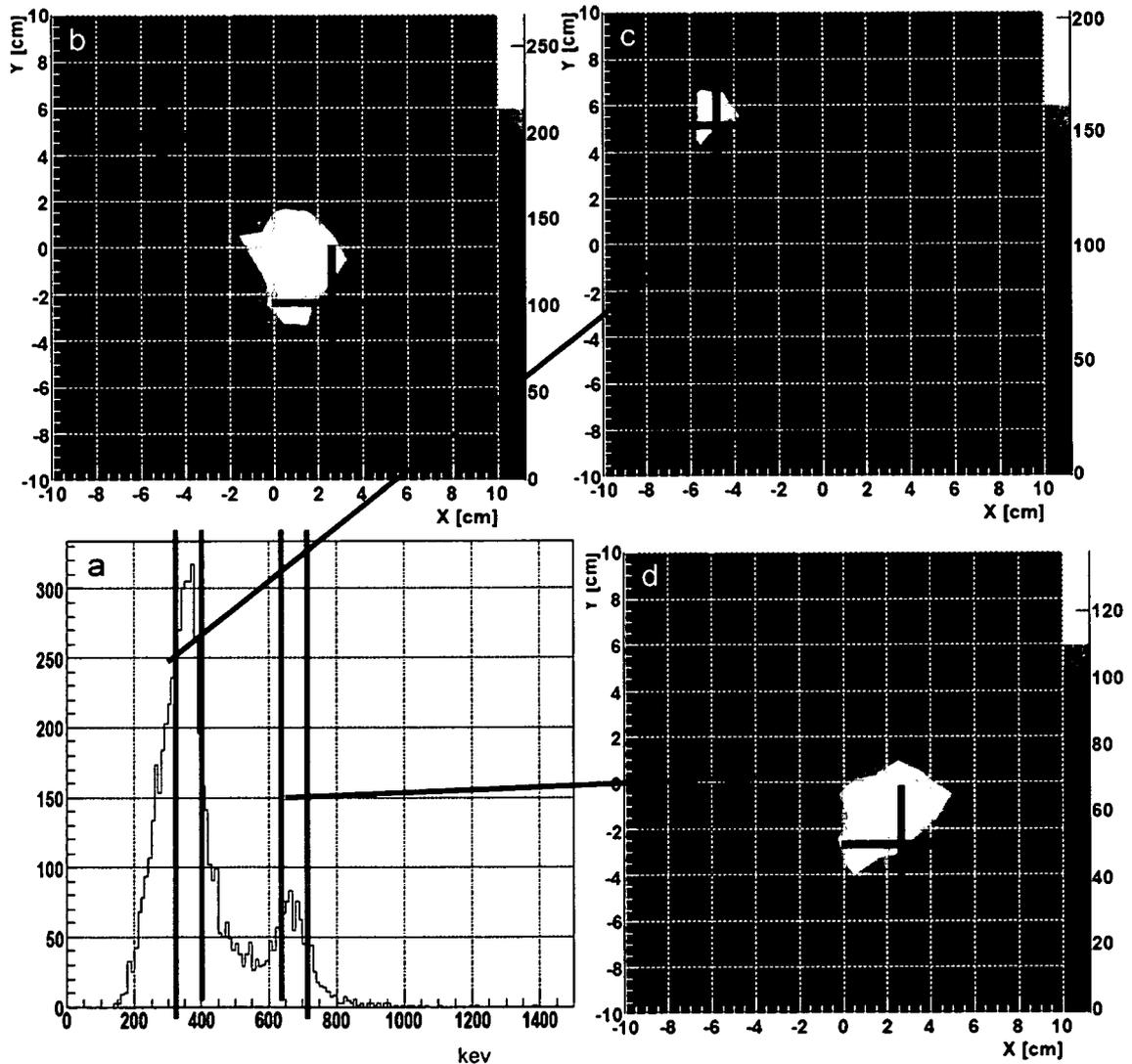

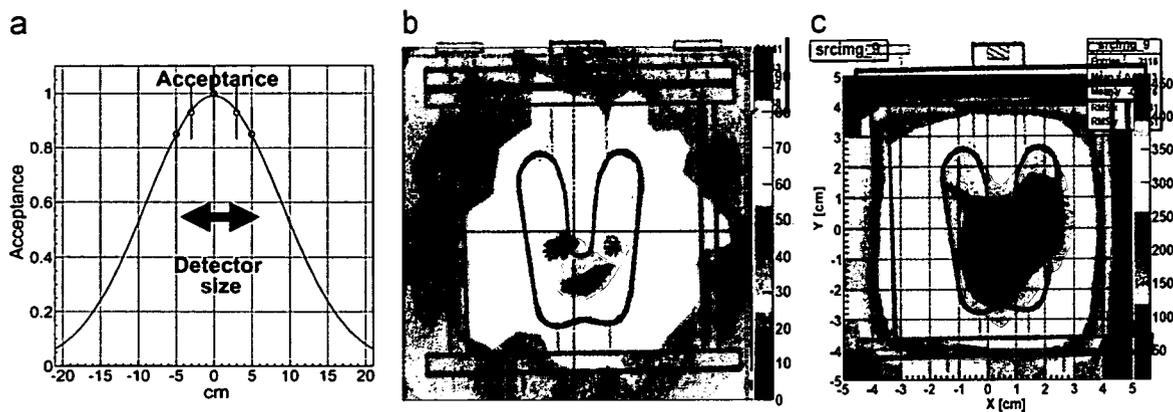Fig. 4. Images obtained by the simultaneous irradiation of [133]Ba: 356 keV and [137]Cs: 662 keV.

Fig. 5. (a) Acceptance of the detector, in which horizontal axis is an arbitrary unit. (b, c) are the images of the phantom of the human thyroid grand filled with [131]I (364 keV) before and after applying the acceptance correction, respectively. The phantom was set on the 20 cm front from the center of the ETCC.

we have obtained the image in the energy region used in nuclear medicine. From this figure, we infer that an image of gamma rays at 511 keV would be separated from that of ^{131}I or [67]Ga. For medical imaging, the recognition of the extended distribution of isotopes in the body is quite inevitable. Using this mobile ETCC, we tried to get the image of the phantom of human thyroid gland for 364 keV gamma rays of [131]I. Before measuring the images, the acceptance of ETCC was measured by moving the ^{131}I point source on the plane at the 20 cm front from the center of the ETCC, and obtained its acceptance plotted in Fig. 5a. One should note the ETCC covers about four times the size of the μ-TPC (the region having a better acceptance than a half of the maximum acceptance). Using this acceptance, the images of a Ø 1 × 30 cm^2 line source filled with ^{131}I were measured by changing its position on vertical and horizontal as shown in Fig. 7. Also, the image of two line sources filled with ^{131}I is presented in Fig. 6 after applying the acceptance correction. Obviously, two lines are distinguished although its shape is distorted. In both Figs. 6 and 7, the acceptance of the detector was crucial for getting the shape of the images. The distortion of the line sources in the under part may indicate the necessity of the more accurate measurement for the acceptance. Based on such a study, the image of the phantom of the human thyroid grand filled with ^{131}I was measured. The phantom was set on the 20 cm front from the center of the ETCC. Fig. 5b and c shows the images before and after applying the acceptance corrections, where you recognize the shape of the phantom although the image is still blurred.

3. Perspective and discussion

As mentioned in Section 1, Compton camera, if its imaging ability were similar to that of PET, would have excellent features for nuclear medicine and molecular imaging, which are not be realized by SPECT and PET. We have developed the ETCC and obtained several images
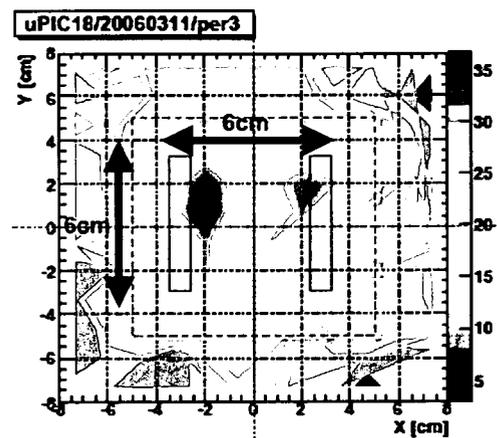

Fig. 6. Image of two line sources filled with [131]I (364 keV), where red lines indicate the positions of two line sources. Two line sources are set on the 20 cm front of the ETCC.

for the extended sources. For reconstructing the extended images, an acceptance correction is found quite significant. While any type of Compton camera is expected to have a wide field of view, our results show that half of the target size is at lease necessary as a detection area to reconstruct the image of the extended target. In the observation for the human organs, more 10 × 10 cm^2 detection area seems to be needed. A Compton camera based on the gas detector easily provides such a large detection area and a flat acceptance. At present, obtained angular resolution is not enough for the imaging of the human organs; however, simulation shows that the angular resolution of the 5° would provide a similar quality of the image to that of PET. In general, a Compton camera provides better images as energy increasing. A simple extrapolation from the angular resolution at 364 keV says that the ETCC will have an angular resolution of ~5° at 511 keV. In July 2006, we have observed phantom images using [18]F (511 keV)-ion and ^{18}F-FGD for a rat, of which results will appear soon. In addition a large μ-TPC (30 × 30 × 15 cm^3) for the ETCC imaging a human body is now being tuned.
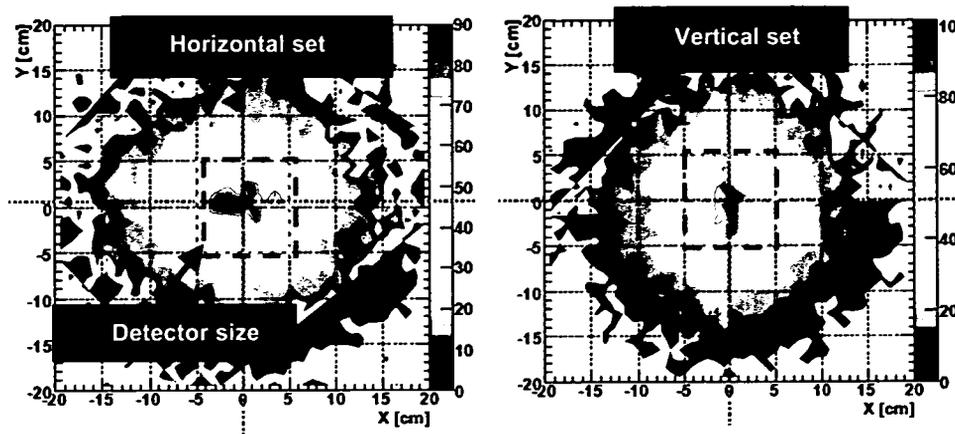
Fig. 7. Images of a long line source (∅ 1 × 30 cm^2) filled with ^{131}I (364 keV) setting on vertical and horizontal, respectively (both are set on the 20 cm front of the ETCC).

Acknowledgments

References

[1] R. Orito, et al., Nucl. Instr. and Meth. A 501 (2003) 408.

[2] T. Tanimori, et al., New Astron. Rev. 48 (2004) 263.
[3] A. Takada, et al., Nucl. Instr. and Meth. A 546 (2005) 258.
[4] T. Kamae, et al., Nucl. Instr. and Meth. A 260 (1987) 254.
[5] T. Tumer, et al., IEEE Trans. Nucl. Sci. NS-42 (1995) 907.
[6] D. Bhattacharya, et al., New Astron. Rev. 48 (2004) 287.
[7] G. Kanbach, et al., New Astron. Rev. 48 (2004) 275.
[8] S. Watanabe, et al., Nucl. Instr. and Meth. A 567 (2006) 150.
[9] A. Ochi, et al., Nucl. Instr. and Meth. A 471 (2001) 264.
[10] T. Nagayoshi, et al., Nucl. Instr. and Meth. A 546 (2005) 457.
[11] R. Orito, et al., IEEE NSS Conf. Rec. (2005) 443.
[12] F. Sauli, et al., Nucl. Instr. and Meth. A 386 (1997) 531.
[13] H. Sekiya, et al., Nucl. Instr. and Meth. A 563 (2006) 49.
[14] H. Kubo, et al., IEEE NSS Conf. Rec. (2005) 371.
[15] T. Tanimori, et al., IEEE NSS Conf. Rec. (2005) 2998.