Applied Radiation and Isotopes 124 (2017) 93–99

Contents lists available at ScienceDirect

Applied Radiation and Isotopes

journal homepage: www.elsevier.com/locate/apradiso

Simulation study of the backward-scattering effect in Compton imager

Guo Xiaofeng[a,b], Xiang Qingpei[a,*], Tian Dongfeng[a], Wang Yi[b], Hao Fanhua[a], Zhang Yingzeng[a], Chu Chengsheng[a], Liang Na[a]

[a] Institute of Nuclear Physics and Chemistry, China Academy of Engineering Physics, Mianyang 621900, China
[b] Department of Engineering Physics, Tsinghua University, Beijing 100084, China

ARTICLE INFO

Keywords:
Compton imager
CdZnTe
Backward-scattering effect
Geant4
Monte Carlo

ABSTRACT

In the field of nuclear medicine, nuclear security and astrophysics, Compton imaging is a promising technique for gamma-ray source imaging. We are developing a Compton imager using two layers of CdZnTe pixel array detectors. In this paper, the backward-scattering effect within such imagers is numerically studied using Geant4 Monte Carlo Package. From images reconstructed based on forward-scattering and backward-scattering imaging events, the imaging precision was investigated in a comparative analysis, in regard to energy resolution and position resolution. Furthermore, to establish a method to use backward-scattering imaging events properly so that the imaging efficiency can be significantly improved, the difference between reconstruction from forward-scattering and backward-scattering imaging events was analyzed to uncover a causal mechanism.

1. Introduction

The Compton-imager concept was first proposed by Schoenfelder et al. (1973) and Todd et al. (1974) in the 1970s. However, limited by detection levels and electronics, such imagers could not be produced at that time. In the past decade, researchers have returned to the Compton imaging technique, which offers promising applications in nuclear safety, nuclear medicine, and astrophysics. To date, a variety of Compton imagers have been developed by several groups in Canada, Japan, Korea, France, Spain, Sweden, and USA. The US groups mainly study Si/NaI (Kurfess et al., 2007), 3D-CdZnTe (Lehner et al., 2004), HPGe (Mihailescu et al., 2007), and other types of imaging systems. The Canadians tend to use scintillator detectors, such as CsI/NaI (Saull et al., 2012) and NaI/$LaBr_3$ (Saull et al., 2010). The Japanese groups are researching the Si/CdTe semiconductor system (Watanabe et al., 2007) and the TPC system (Kubo et al., 2006), which is able to track electrons so that the imaging precision can be improved. The South Koreans are committed to multimode imaging using the combination of a coded aperture and a Compton imager (Lee and Lee, 2014a, 2014b). After years of research, currently the Si/NaI system and the 3D-CdZnTe system developed in the USA and the CsI/NaI system developed in Canada have shown some practical applications in the search for gamma-ray sources.

CdZnTe detectors have good energy resolution at room temperature. With the development of detectors and electronics technology, CdZnTe detectors moreover have achieved moderate position resolution. As a result, the CdZnTe detectors are proving to show promise for Compton imaging. The University of Michigan, USA, has obtained images with a single 3D-CdZnTe detector (Zhu, 2012). However, using a single detector for imaging requires small distances between the two interactions of imaging events, which leads to a degradation of imaging precision. Considering the high price and complex imaging algorithm of the 3D-CdZnTe detector, we have decided to develop a Compton imager with two layers of CdZnTe pixel array detectors. With the front layer thinner than the back layer, the front layer functions mainly as a scattering layer and the back layer as an absorber.

In the Compton imager, there are two types of positive imaging events that can be used for image reconstruction: forward-scattering imaging events (FSIEs) and backward-scattering imaging events (BSIEs). The FSIEs are defined as events in which Compton scattering of gamma-rays from a source occurs in the front layer followed by a subsequent absorption of the scattered photon in the back layer. Conversely, the BSIEs are defined as events in which Compton scattering occurs in the back layer with absorption occurring in the front layer. Generally, in reconstructions, all imaging events are assumed to be FSIEs, which leads to a miss-reconstruction of BSIEs, and in turn degrades the imaging performance. We term this phenomenon 'backward-scattering effect' (BSE).

In particular, backward-scattering effect occurs easily in Compton imagers where the front layer consists of a high-Z material, such as found in the CsI/NaI (Saull et al., 2012) and the NaI/$LaBr_3$ (Saull et al., 2010) Compton imagers developed in Canada. Their reports mention

* Corresponding author.
E-mail address: xiangqingpei@163.com (X. Qingpei).

http://dx.doi.org/10.1016/j.apradiso.2017.03.019
Received 27 January 2017; Received in revised form 16 March 2017; Accepted 20 March 2017
Available online 22 March 2017

that BSIEs will lead to the miss- reconstruction of Compton scattering angles, and hence energy restrictions have been used to reject BSIEs in reconstruction. However, this appears wasteful as BSIEs may still be useful for image reconstruction despite imaging precision being worse than that based on FSIEs. Our goal is to understand how BSIEs degrade imaging precision; its causal mechanism may be helpful in finding a suitable means to exploit better reconstruction based on BSIEs so that gamma-ray imaging efficiency can be improved evidently.

In our study, a Compton imager comprising two layers of CdZnTe pixel array detectors was modeled using Geant4 (Agostinelli et al., 2003). With this imager, the influence of backward-scattering effect on imaging performance was quantitatively studied. The precision of images reconstructed based on FSIEs and BSIEs were comparatively assessed. The underlying mechanism differentiating the two types of imaging events was analyzed theoretically.

2. Simulation setup

2.1. Compton imager modeling

The Compton imager consists of two layers of CdZnTe pixel array detectors (Fig. 1). Each layer has a 5×5 detector array of effective area 50×50 mm^2. Each detector is divided into 8×8 pixels with a minimal position resolution of 1.25 mm. The detectors in the front layer have a thickness of 2 mm and mainly produce scatter, whereas the detectors in the back layer have a thickness of 5 mm and are mainly used as absorber. A ^{137}Cs point source of gamma-rays is placed 10 cm away from the midpoint of the front layer. The distance between the two layers is adjustable.

In Fig. 1, the red and blue lines represent a typical FSIE and BSIE. The ratio of these two imaging events primarily depends on the properties of the Compton imagers used. If the front layer of the Compton imager is made of low-Z material, the number of BSIEs will be much smaller than that of FSIEs, so that backward- scattering effect is negligible. However, if the front layer consists of high-Z material, the fraction of BSIEs increases and hence backward-scattering effect will be evident.

2.2. Algorithm definitions

In our study, a simple back projection algorithm was used to reconstruct the source image. As is well known, when a gamma-ray scatters in detector, the scattering angle θ can be calculated using the Compton scattering formula

$$\cos\theta = 1 - \frac{m_0c^2 \cdot E_e}{(E_e + E_\gamma) \cdot E_\gamma} \tag{1}$$

where $m_0c^2 = 511$ keV, E_e is the energy of the recoil electron, and E_γ is the energy of the scattered photon.

Moreover, assuming that S, C, and A are the respective point locations of the gamma-ray source, Compton scattering interaction,

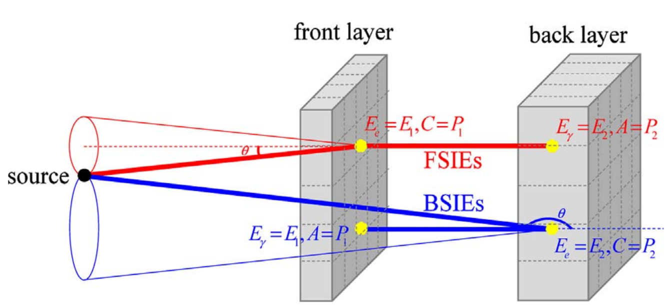

Fig. 1. Schematic of a Compton imager comprising two layers of CdZnTe pixel array detectors. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

and absorption of the scattered photon, then these three points satisfy the geometric relation

$$\cos\theta = \frac{\overrightarrow{SC} \cdot \overrightarrow{CA}}{|\overrightarrow{SC}| \cdot |\overrightarrow{CA}|}. \tag{2}$$

From Eqs. (1) and (2), the point-source position S from one event can be located to within the surface of a cone. With the intersection of multiple cones reconstructed from many imaging events, the source position can be further determined to an intersection point.

In Fig. 1, E_1 and P_1 represent the deposited energy and its position in the front layer; similarly, E_2 and P_2 represent the deposited energy and its position in the back layer. Corresponding to the two types of imaging events, for image reconstruction there are two algorithms termed forward and backward. The forward algorithm reconstructs imaging events as FSIEs, for which $E_e = E_1$, $E_\gamma = E_2$, $C = P_1$, $A = P_2$; the backward algorithm reconstructs imaging events as BSIEs, for which $E_e = E_2$, $E_\gamma = E_1$, $C = P_2$, $A = P_1$. Clearly, FSIEs and BSIEs can only be accurately reconstructed using their respective algorithms.

2.3. Selection of imaging events

Considering the energy resolution, the deposited energy E will be broadened as determined by its full- width-at-half-maximum (*FWHM*)

$$FWHM = a + b\sqrt{E} = 2.355\sigma \tag{3}$$

where E is the energy deposited in detectors and σ is the standard deviation of the Gaussian function. The two parameters, a and b, are determined by the energy resolution of the detectors. For the CdZnTe pixel array detectors produced by IMDETEK Corporation Ltd., the energy resolution is 5.13% for ^{241}Am (59.5 keV) and 1.64% for ^{137}Cs (662 keV), giving: $a = -0.2892$, $b = 0.4332$. In respect to the position resolution, the position of each interaction should be replaced by the center of the corresponding pixel for lateral direction. For depth direction, the position resolution of CdZnTe is generally calculated by anode-to-cathode ratio or drift time whose precision is sub-millimeter. Therefore, for simulation, the position resolution of depth direction is set to 0.5 mm in approximation.

Basically, the ideal imaging event in the Compton imager is one where the gamma-ray from the point source scatters only once in the front layer and is absorbed in the back layer through a photoelectric effect. However, the time sequence of the scattering interaction and absorption interaction cannot be distinguished experimentally. In consequence, imaging events can selected only if the following three requirements are simultaneously met: (1) There must be energy deposition in both the front layer ($E_1 > 0$) and the back layer ($E_2 > 0$); (2) The total energy ($E_1 + E_2$) should be within 662 keV $\pm$ 3σ (14 keV); (3) Energy must only be deposited in a single pixel for both the front layer and the back layer. The restriction to a single pixel here is to ensure accuracy in scattering and absorption positions.

Theoretically, by stipulating these three requirements, the two types of positive imaging events, FSIEs and BSIEs, will be filtered. Nonetheless, some false imaging events (FIEs) pass selection. For example, a gamma-ray from the source is absorbed through the photoelectric effect in one layer, but the photoelectron escapes or emits a bremsstrahlung photon, which is then absorbed in the other layer. Alternatively, the gamma-ray from the source scatters more than once in a single pixel of one layer, and then is absorbed in a single pixel of the other layer.

3. Results and discussion

3.1. Analysis of imaging types

In simulations to obtain the ratio of each type of imaging event, 10^9