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# Depth discrimination method based on a multirow linear array detector for push-broom Compton scatter imaging

Yantao Liu [a,b], Zhiming Zhang [a,b], Daowu Li [a,b], ChuangXin Ma [a,b], Cunfeng Wei [a,b], Meiling Zhu [a,b], Lei Shuai [a,b], Tingting Hu [a,b], Baotong Feng [a,b], Pei Chai [a,b], Xianchao Huang [a,b], Haohui Tang [a,b], Ting Li [a,b], Kai Zhuang [a,b], Xiaopan Jiang [a,b], Yingjie Wang [a,b], Yiwen Zhang [a,b], Wei Zhou [a,b], Shifeng Sun [a,b], Long Wei [a,b,*]

[a] *Key Laboratory of Nuclear Analytical Techniques, Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, China*
[b] *Beijing Engineering Research Center of Radiographic Techniques and Equipment, Beijing 100049, China*

HIGHLIGHTS

- We devise a depth discrimination method for *push-broom* Compton scatter imaging.
- Depth of sample is indicated by comparing signal proportions of different modules.
- The depth discrimination is linked to different measurement geometries.
- A multirow linear array detector based on XP1452 and LYSO was developed.
- Simulation model is built using GEANT4 to support the method well.

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ABSTRACT

A depth discrimination method is devised based on a multirow linear array detector for *push-broom* Compton scatter imaging. Two or more rows of detector modules are placed at different positions towards a sample. An improved parallel-hole collimator is fixed in front of the modules to restrict their fields of view. The depth information could be indicated by comparing the signal differences. In addition, an available detector and several related simulations using GEANT4 are given to support the method well.



## 1. Introduction

Compton scatter imaging (CSI) is a noninvasive imaging technique based on the Compton scattering effect, which was discovered by Compton in 1923. It was first described in the medical field by Lale (1959) and then applied in many nondestructive testing fields, such as corrosion detection in aircraft (Dunn and Yacout 2000), food checks (McFarlane et al., 2003), buried landmine detection (Yuka et al., 2006), security inspection (Vogel 2007a,b), and historical exploration (Harding and Harding 2010). Unlike transmission imaging, CSI allows a flexible choice of measurement geometries. Its radiation source and detectors can be arranged in any direction, especially on the same side of a sample. Therefore, CSI is applicable in detecting the sample underground or in walls where transmission imaging fails. It is also suitable for a surface measurement of large, thick, bulky objects. Moreover, CSI is highly sensitive to light-element materials such as hydrogen, carbon, nitrogen, and oxygen. Therefore, it could provide a high-contrast image of organic contraband such as petrol, drugs, explosives, etc. Finally, scatter voxels could be directly located using the intersection points of primary photons and scattered photons.

However, CSI is inferior compared to transmission imaging in its signal-to-noise ratio (SNR). The quantity of photons backscattered (scatter angle beyond 90°) to a detector is less than 0.8% of those

* Corresponding author at: Chinese Academy of Sciences, Key Laboratory of Nuclear Analytical Techniques, Institute of High Energy Physics, Beijing 100049, China. Tel.: +86 10 88236347; fax: +86 10 88236413.
*E-mail addresses:* ytliu@ihep.ac.cn (Y. Liu), weil@ihep.ac.cn (L. Wei).

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transmitted, in theory, to its counterpart detector (Park et al., 2006). These scattered photons would be further limited by the locating devices in front of the detector. The scatter energies of photons are less than the primary energy; therefore, they are more susceptible to noises from the radiation source and the detector. To improve the SNR, it usually increases the intensity of primary photons, expands effective areas of the detector, and/or prolongs sampling time in CSI systems.

To realize positioning and imaging, an appropriate scheme is required to scan the sample. One main scan scheme in present CSI systems is called *flying spot* (Towe and Jacobs 1981a,b; Herr et al., 1994). It uses a pencil beam of X-rays to scan the sample in a point-by-point method. In this way, it can provide a high-resolution three-dimensional (3D) image of the sample, but has a low utilization efficiency of the radiation source and a long sampling time. The other scan scheme is called *push-broom* (Yuka et al., 2006; Park et al., 2006; Guangzhi Sun et al., 2008) and uses a fan beam of X-rays and linear array detectors directly. This scheme enhances the utilization efficiency of the radiation source and reduces the sampling time. However, it only provides a superposed two-dimensional (2D) projection without depth information in existing systems. More details of the scan schemes are compared in Section 3.

In this work, a method was devised to achieve a primary depth discrimination based on a multirow linear array detector for *push-broom* CSI. The detector was composed of two or more rows of modules, an improved parallel-hole collimator, and the corresponding data acquisition system (DAQ). The modules were placed in different directions towards a sample to receive scattered signals independently. The collimator was fixed in front of the modules to restrict their fields of view (FOVs). When Compton scattering occurred at different depths, scattered photons would be distributed into the adjacent modules in different proportions. The proportions indicated depth information using a special algorithm. In addition, an available detector was presented and several related simulations using GEANT4 (Miceli et al., 2007; Sullivan et al., 2008; Harkness et al., 2009; Trinci et al., 2010; Cirrone et al., 2010; Rossi et al., 2011) were given that supported the method well.

## 2. Characteristics of Compton scattering

Compton scattering and photoemission are two main competitive interactions when photon energy is below 1 MeV. In addition, Compton scattering dominates the reaction cross section from 100 keV to 1 MeV in aluminum (a representative of the low and moderate atomic number $Z$ materials) (Harding and Harding 2010). The scatter energy and the angular distribution of the Compton scatter for stationary, free electrons are calculated by the two formulas below:

$$E(\theta)=[1/E_0+(1-\cos\theta)/m_ec^2]^{-1} \tag{1}$$

$$d\sigma/d\Omega=(r_e^2/2)\eta^2(\eta+\eta^{-1}-\sin^2\theta) \tag{2}$$

In Eqs. (1) and (2), $\theta$ is the scatter angle; $d\sigma/d\Omega$ is the Klein–Nishina cross section; $E_0$ and $E(\theta)$ are the primary energy and the scatter energy of photons, respectively; $\eta$ is defined as the ratio of $E(\theta)$ to $E_0$ ($E(\theta)/E_0$); $m_ec^2$ is the rest mass energy of electron (511 keV); and $r_e$ is the classical electron radius (2.82 fm).

If photons were emitted from an X-ray tube of 450 kVp, their average primary energy would be approximately 150 keV, using the theory of bremsstrahlung. When the scatter angle $\theta$ was equal to 135°, and the primary energies $E_0$ ranged from 50 to 450 keV, the corresponding scatter energies $E(\theta)$ and the linear attenuation coefficients $\mu$ of $Lu_2SiO_5$ are listed in Table 1. It was found that the average scatter energy was approximately 99.9 keV and the corresponding linear attenuation coefficient was approximately 22.6 cm$^{-1}$. Therefore, in this case, a $Lu_2SiO_5$ scintillator of 3 mm depth could provide enough stopping power for scattered photons.

**Table. 1**
The scatter energies and the linear attenuation coefficients of scintillator $Lu_2SiO_5$ in different primary energies ($\theta$=135°, $\rho$=7.3 g/cm$^3$).

| Primary energy (keV) | Scatter energy (keV) | Linear attenuation coefficient (cm$^{-1}$) [a] |
|---|---|---|
| 50 | 42.8 | 44.2 |
| 100 | 74.9 | 47.6 |
| 150 | 99.9 | 22.6 |
| 200 | 119.8 | 14.3 |
| 300 | 149.7 | 8.2 |
| 450 | 179.6 | 5.3 |

[a] Data were employed in linear interpolation on the original data from the National Institute of Standards and Technology (http://physics.nist.gov/PhysRefData/FFast/html/form.html).

**Table 2**
The scatter energies and the Klein–Nishina cross sections at different scatter angles ($E_0$=150 keV, $\rho$=7.3 g/cm$^3$).

| Scatter angle (°) | Scatter energy (keV) | Klein–Nishina cross section (mb) |
|---|---|---|
| 90 | 116.0 | 25.3 |
| 105 | 109.5 | 24.7 |
| 120 | 104.1 | 26.5 |
| 135 | 99.9 | 29.4 |
| 150 | 96.9 | 32.2 |
| 165 | 95.1 | 34.3 |
| 180 | 94.5 | 35.0 |

When the primary energy $E_0$ equaled to 150 keV, and the scatter angles $\theta$ ranged from 90° to 180°, the corresponding scatter energies $E(\theta)$ and the Klein–Nishina cross sections $d\sigma/d\Omega$ were listed in Table 2. The scatter energies and the cross sections varied to a small extent. This variation could be corrected or even overlooked, especially for a detector of a limit solid angle. The angular distribution of Compton scatter could be assumed to be an isotropic distribution in the below calculations and simulations.

When considered in materials, electrons were not free but were bound by nuclei. Therefore, an incoherent atomic scatter function $S(q, Z)$ (Sharaf 2001; Hubbell et al., 1975; Böke 2013; Massaro and Matt 1986), which accounted for electron binding energy effects with the photon momentum transfer $q$, should be considered in the actual scattering cross section. Its value was tabulated for all elements by Hubbell et al. (1975). For low $Z$ materials, $S(q, Z)$ was considered equal to $Z$ because the electron binding energy was small. Therefore, the intensity of scattered photons was directly proportion to the electron density of materials. For high $Z$ materials, $S(q, Z)$ did not trend to $Z$ but instead rapidly decreased. The intensity of scattered photons was small.

## 3. Scan schemes of Compton scattering imaging

### 3.1. Point-by-point scan scheme

The first CSI system developed by Lale (1959) adopted a simple point-by-point scan scheme. A narrow pencil beam was collimated by beam collimators directly to hit a sample, while a single