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Measurement Experiment of CLYC-based Rotational Modulation Collimator (RMC) System using a Gamma-ray Source

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1. Introduction

The introduction of Cs_2LiYCl_6:Ce (CLYC)-based rotational modulation collimator (RMC) has been shown as effective method for gamma-ray/neutron dual-particle imager and a rough but economical first-line detection tool for radioactivity [1]. However, due to the intrinsic artifact in a symmetric design, we cannot distinguish modulation patterns of two source positions, one from the other, which are symmetrically located with respect to the rotational axis of the mask [2]. To overcome the challenge given by the common symmetric mask design, we suggest the asymmetric mask design [3]. In this study, measurement experiments were taken in the mid-range field (source-to-front mask distance 100 cm) using a gamma-ray source. The fabricated CLYC-based RMC was tested with a ^{133}Ba source and verified that the asymmetric mask approach via measurement experiments. In addition, measurement results were used to reconstruct images of a source distribution, demonstrating CLYC-based RMC's potential as a dual-particle imager.

2. Methods and Results

2.1 CLYC-based RMC

The RMC structural design for this research consists of mainly two collimator masks and CLYC detector. As the masks rotate together, the open area made by slits will appear to open and close, causing the incoming radiation flux counted in the detector to be modulated.

In the detector part, we adopted a CLYC scintillation detector for dual-particle detection. The CLYC shows excellent performance in the identification of gamma rays and neutrons using pulse shape discrimination (PSD) [4]. The detection of thermal neutron is based on the ^{6}Li(n,α)T reaction. In our system, the detector consists of a 2”×2” cylindrical CLYC crystal, coupled to a R6233-100 photomultiplier tube.

For collimator masks, we designed a laminated structure which combines a 1 cm-thick lead (Pb) mask and a 0.2 cm-thick borated polyethylene (BPE) mask. As results of Monte Carlo N-Particle (MCNP version 6.1) simulations [5], the shielding efficiency for 356 keV gamma rays was estimated to be ~95% when 1 cm-thick Pb was used, and the shielding efficiency of 0.2 cm-thick BPE mask was estimated to be 100% for 0.025 eV thermal neutrons.

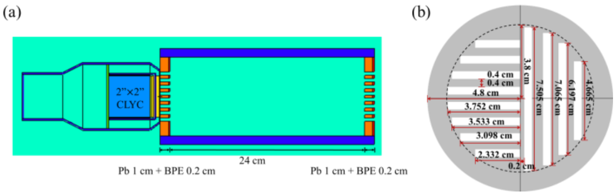

Fig. 1. Schematic of CLYC-based RMC: (a) CLYC-based RMC system and (b) asymmetric-mask design

2.2 Measurement Experiment: Gamma-ray source

Fig. 2 is pictures of the experimental setup. To test the fabricated RMC's ability, a 10.64 μCi ^{133}Ba source was used. The gamma-ray source is standard calibration sources of R-type rod (Eckert & Ziegler, Germany). The detection time was 20 minutes (live time) at each of the rotation conditions with an interval of 10°. For obtaining modulation patterns, the 356 keV gamma rays were analyzed to calculate the peak area under the full-energy absorption peak. The measurement results were compared with MCNP6 results.

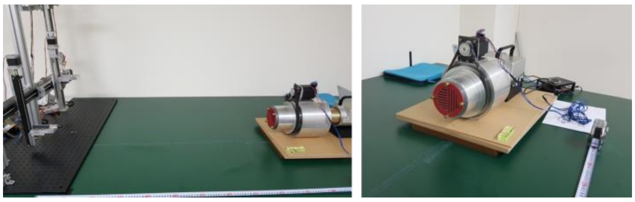

Fig. 2. Experimental setup: Source-to-front-mask distance is 100 cm.

The modulation patterns from the experimental, MCNP6 are shown in the Fig. 3. The results show good agreements between MCNP6 and measurement experiments. In case of asymmetric mask, the period of modulation patterns was 360°. This means that two source positions which are symmetric with respect to the rotational axis of the mask can be distinguished in modulation patterns [2]. Therefore, maximum-likelihood estimation maximization (MLEM) algorithm can estimate source position correctly.

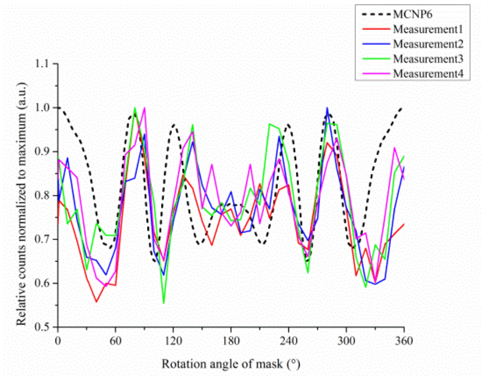

Fig. 3. A modulation pattern of 356 keV gamma rays: source position at (5,0,100) cm. (0,0,0) is set to be the rotation axis of the front mask face.

2.3 Image reconstruction

For the reconstruction of the radiation image, we employed the MLEM algorithm. Modulation patterns calculated by the MCNP6 were used as a system matrix, and the modulation patterns obtained by the measurements were used for inputs for the imaging algorithm. System matrices were generated for 11 by 11 pixels, and the pixel interval was determined 2 cm. The MLEM equation is given as

$$\lambda_j^{n+1} = \frac{\lambda_j^{n}}{\sum_i a_{ij}} \sum_i a_{ij} \left(\frac{y_i}{\sum_j \lambda_j^{n} a_{ij} + b_i} \right) \qquad (1)$$

where λ is the value of maximum-likelihood estimation (MLE), a_{ij} is the system matrix (i is the mask position of rotation and j is the source position), y is the input data and b is the background. The iteration was performed for 1,000 times, and reconstructed images were analyzed in terms of the signal to noise ratio (SNR) [6]:

$$SNR = 10 \cdot \log_{10} \left[\frac{\sum_0^{n_x} \sum_0^{n_y} [t(x,y)]^2}{\sum_0^{n_x} \sum_0^{n_y} [r(x,y) - t(x,y)]^2 \; / \; N} \right] \qquad (2)$$

where r(x,y) is the reference image which contains actual source position in the image, and t(x,y) is the test image which contains an expected source position obtained by MLEM and n is the total number of pixels in the image.

Fig. 4 shows reconstructed images of the 356 keV gamma rays. In these figures, squares show estimated source locations, and the value of MLE is shown in terms of the brightness. The measurement results show a good performance in the estimation of the source distribution. The values of SNR were (a) 13.6, (b) 14.1, (c) 15.3, and (d) 14.1 respectively.

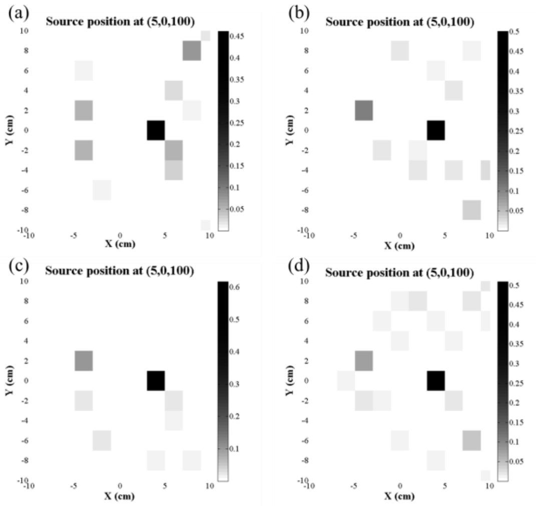

Fig. 4. 2-D reconstructed images: source located at (5,0,100) cm.

3. Conclusions

We demonstrated the feasibility of a CLYC-based RMC system for dual-particle imager by measurement experiments using a gamma-ray source. The CLYC-based RMC is expected to show good performances as a gamma-ray/thermal neutron dual-particle imager. It can be utilized first-line detection tool for radioactivity.

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