Development and Preliminary Results of a Large-Pixel Two-Layer LaBr3 Compton Camera Prototype

Authors: Minghao, Dong, Zhiyang, Yao, Xiao Yongshun, Yongshun, Xiao

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Abstract

Objective. Lanthanum bromide (LaBr3) crystal has a high energy resolution and time resolution and has been used in Compton cameras (CCs) over the past few decades. However, LaBr3 crystal arrays are difficult to process because LaBr3 is easy to crack and break; thus, few LaBr3-based CC prototypes have been built. In this study, we designed and fabricated a large-pixel LaBr3 CC prototype and evaluated its performance with regard to position, energy, and angular resolution. Approach. We used two 10×10 LaBr3 crystal arrays with a pixel size of 5 mm $\times$ 5 mm, silicon photomultipliers (SiPMs), and corresponding decoding circuits to construct our prototype. Additionally, a framework based on a Voronoi diagram and a lookup table was developed for list-mode projection data acquisition. Monte Carlo (MC) simulations based on Geant4 and experiments were conducted to evaluate the performance of our CC prototype. Main results. The lateral position resolution was 5 mm, and the maximum deviation in the depth direction was 2.5 and 5 mm for the scatterer and absorber, respectively. The corresponding measured energy resolutions were 7.65% and 8.44%, respectively, at 511 keV. The experimental results of 137Cs point-like sources were consistent with the MC simulation results with regard to the spatial positions and full widths at half maximum (FWHMs). The angular resolution of the fabricated prototype was approximately 6° when a point-like 137Cs source was centrally placed at a distance of 5 cm from the scatterer. Signification. We proposed and investigated a large-pixel LaBr3 CC for the first time and verified its feasibility for use in accurate spatial positioning of radiative sources with a high angular resolution. The proposed CC can satisfy the requirements of radiative source imaging and positioning in the nuclear industry and medical applications.

Full Text

Development and Preliminary Results of a Large-Pixel Two-Layer $LaBr_3$ Compton Camera Prototype

Minghao Dong[1,2], Zhiyang Yao[1,2], Yongshun Xiao*[1,2]
[1]Department of Engineering Physics, Tsinghua University, Beijing, 100084, China
[2]Key Laboratory of Particle & Radiation Imaging (Tsinghua University), Ministry of Education, Beijing, China
*Correspondence to: xiaoysh@mail.tsinghua.edu.cn

Abstract

Objective. Lanthanum bromide ($LaBr_3$) crystal exhibits high energy resolution and time resolution and has been employed in Compton cameras (CCs) for several decades. However, $LaBr_3$ crystal arrays are difficult to fabricate because $LaBr_3$ is prone to cracking and breaking; consequently, few $LaBr_3$-based CC prototypes have been constructed. In this study, we designed and fabricated a large-pixel $LaBr_3$ CC prototype and evaluated its performance in terms of position, energy, and angular resolution.

Approach. We constructed our prototype using two 10 × 10 $LaBr_3$ crystal arrays with a pixel size of 5 mm × 5 mm, silicon photomultipliers (SiPMs), and corresponding decoding circuits. Additionally, we developed a framework based on a Voronoi diagram and a lookup table for list-mode projection data acquisition. Monte Carlo (MC) simulations based on Geant4 and experimental measurements were conducted to evaluate the performance of our CC prototype.

Main Results. The lateral position resolution was 5 mm, and the maximum deviation in the depth direction was 2.5 mm and 5 mm for the scatterer and absorber, respectively. The corresponding measured energy resolutions were 7.65% and 8.44%, respectively, at 511 keV. The experimental results for ^{137}Cs point-like sources were consistent with the MC simulation results regarding spatial positions and full widths at half maximum (FWHMs). The angular resolution of the fabricated prototype was approximately 6° when a point-like ^{137}Cs source was centrally placed at a distance of 5 cm from the scatterer.

Significance. We proposed and investigated a large-pixel $LaBr_3$ CC for the first time and verified its feasibility for accurate spatial positioning of radioactive sources with high angular resolution. The proposed CC can satisfy the requirements for radioactive source imaging and positioning in nuclear industry and medical applications.

Keywords: Compton camera, large pixel, gamma camera, $LaBr_3$ detector, prototype evaluation.

Introduction

To overcome the low detection efficiency of traditional imaging systems for high-energy gamma rays, the Compton camera (CC) was proposed in 1974 [1]. The CC employs electronic collimation rather than mechanical collimation, thereby offering a wider field of view (FOV) and higher detection efficiency. It can detect gamma rays over a broad energy range of 100 keV–10 MeV, which encompasses the natural radioactivity of nuclear materials and waste [2–4] as well as typical gamma-ray energies used in medical applications such as radiopharmaceutical imaging [5–8] and prompt gamma imaging [9–11]. The earliest CC prototype was a single-layer system that could distinguish photon scattering and absorption positions using a single layer of scintillator detector. However, due to limitations in detector materials and data acquisition technology, the CC was not practically applied at that time.

To improve CC performance, several prototypes have been proposed and constructed over the past few decades. CC prototypes can be divided into two main categories: single-layer and multilayer systems. Single-layer CCs are similar to the earliest prototypes but benefit from recent advances in detector materials and circuit readout technology. Among these, the three-dimensional (3D) cadmium zinc telluride (CZT) CC represents the state-of-the-art in single-layer CCs. Considerable research has been conducted on 3D CZT CCs, and functional prototypes have been developed [12]. Single-layer CCs offer advantages of a large FOV, high spatial resolution, and high energy resolution; however, the detector material is expensive. Additionally, the distance between scattering and absorption positions is much shorter than in multilayer CCs, resulting in larger deviations in the spatial orientation of Compton cones.

Multilayer CCs determine scattering and absorption positions in separate detectors, thereby receiving only photons incident from specific directions. Multilayer CCs have been developed and applied in the detection of radioactive materials [13] and prompt gamma imaging during hadron therapy [14]. Among multilayer CCs, three-or-more-layer systems offer high detection efficiency but are more expensive than two-layer CCs while providing comparable performance; furthermore, the probability of three-point interaction events is far lower than that of two-point interaction events [15]. Consequently, two-layer CCs represent the mainstream architecture for multilayer systems.

Scintillator materials for CCs have been extensively researched in recent years [16–19]. Scintillator materials provide relatively high detection efficiency and time resolution. Various scintillators exist, such as LYSO, GAGG, and lanthanum bromide ($LaBr_3$), each with distinct advantages and disadvantages. Different scintillators have therefore been employed in CCs for various applications. LYSO and GAGG crystals have higher densities (7.2 and 6.6 g/cm^3, respectively) than $LaBr_3$. However, LYSO exhibits background radiation ranging from 88 to 597 keV, which degrades energy resolution—particularly for detecting natural radioactivity [20]. Additionally, GAGG has a long light decay time of approximately 90 ns, making it more prone to erroneous coincidence signals compared with the 20-ns coincidence time window used in this study. The $LaBr_3$ scintillator has a light decay time of 20 ns and relatively low intrinsic background radiation. Moreover, it achieves the highest energy resolution among these three outstanding and cost-effective scintillators. Extensive research has been conducted on $LaBr_3$ scintillators due to their excellent performance [21–24]; therefore, $LaBr_3$ was selected for our CC prototype.

Existing CC prototypes typically employ small pixel sizes (e.g., 1 mm × 1 mm) and large numbers of pixels per layer (e.g., several hundred pixels per layer) to obtain accurate reconstruction results. Little research has investigated the influence of large pixel sizes on CC reconstruction accuracy. Additionally, $LaBr_3$ crystals are prone to cracking and breaking during processing, making it difficult to fabricate small-pixel $LaBr_3$ crystal arrays. Among $LaBr_3$-based CC research, only MACACO employed a small pixel size (3 mm × 3 mm) [15].

Although large pixel sizes result in lower position resolution, a promising solution is to use reconstruction algorithms with resolution recovery (RR). Recently, RR-based reconstruction algorithms have proven effective in correcting errors caused by the limited resolution of practical CCs [25, 26]. Among these, RR-based maximum likelihood expectation-maximization (MLEM) [6] and origin ensemble (OE) algorithms [7] have attracted considerable attention, with optimization methods such as graphics processing unit (GPU) acceleration [6] and deep learning [8] being applied. Furthermore, radioactive source imaging with a CC prototype during nuclear decommissioning based on the subset-driven origin ensemble with resolution recovery (SD-OE-RR) algorithm has been demonstrated [3]. Thus, CC systems with large pixel sizes are expected to reconstruct images with high spatial resolution when aided by RR-based reconstruction algorithms, making them promising for practical applications.

In this study, we developed and evaluated a two-layer $LaBr_3$ CC prototype with large pixel size for nuclear material and waste detection. Two $LaBr_3$ crystal arrays with a relatively large pixel size of 5 mm × 5 mm × 5 (10) mm, silicon photomultipliers (SiPMs), and encoding circuits were used to construct our prototype. We employed a data-acquisition card (DAQ) to select and decode coincidence events and developed a framework to obtain list-mode data from time-series projection data, including interaction positions and energies deposited in the scatterer and absorber. Finally, we evaluated our prototype's performance through simulations and preliminary experiments.

2.1 Structure of Two-Layer $LaBr_3$ Compton Camera Prototype

The $LaBr_3$ CC prototype consisted of a scatterer and an absorber, both with identical cross-sectional areas. As shown in Figure 1 [Figure 1: see original paper], the $LaBr_3$ detectors comprised a 10 × 10 $LaBr_3$ array with thicknesses of 5 mm for the scatterer and 10 mm for the absorber (Kinheng Crystal, Shanghai, China) and an encoding circuit module containing SiPMs (TOFTEK, Wuxi, China). The pixel size of the $LaBr_3$ array was 5 mm × 5 mm × 5 (10) mm, with pixels separated by 0.1-mm $BaSO_4$ spacers. A 1-mm-thick glass plate and a 1.2-mm-thick Al shell were used for vacuum packaging. The volume of the $LaBr_3$ array was 56.4 mm × 56.4 mm × 9.3 (14.3) mm. Both layers featured an encoding circuit module behind the scintillator arrays, which included an 8 × 8 SiPM array and a 4-channel output encoding circuit. The voltage values of the 64-channel signals output from the SiPMs were proportional to the number of scintillation photons distributed across the corresponding 64 SiPM pixel areas. The 4-channel output encoding circuit transferred the 64-channel SiPM signals to 4-channel outputs through a resistance weighting network.

The output signals were then input into the DAQ (TOFTEK, Wuxi, China). Eight signals (four channels from the scatterer and four from the absorber) were simultaneously input into the same DAQ, which output the total voltage values of the eight signals in each time window. The two layers were fixed by a 3D-printed resin bracket. The distance between the centers of the two $LaBr_3$ arrays was adjustable, with a default value of 50 mm.

Figure 1. Fabricated two-layer $LaBr_3$ CC prototype: (a) structure diagram; (b) photograph.

Figure 2 [Figure 2: see original paper]. Encoding circuit and position decoding diagram: (a) structure diagram of the $LaBr_3$ CC detector; (b) photograph of the $LaBr_3$ detector.

2.2 List-Mode Data Acquisition through Lookup Table

The DAQ output a data row containing nine integers: a timestamp and V_1–V_8. V_1–V_8 represented the eight voltage signals, with V_1–V_4 corresponding to scatterer signals and V_5–V_8 to absorber signals. The subscripts from smallest to largest corresponded to A, B, C, and D in Figure 2.

The positions in scatterplots (x, y) where scintillation photons were generated and detected were calculated using the Anger camera method [27]:

$$x_s = G \times \frac{V_1 - V_3 + V_2 - V_4}{V_1 + V_2 + V_3 + V_4}$$

$$y_s = G \times \frac{V_1 - V_2 + V_3 - V_4}{V_1 + V_2 + V_3 + V_4}$$

$$x_a = G \times \frac{V_5 - V_7 + V_6 - V_8}{V_5 + V_6 + V_7 + V_8}$$

$$y_a = G \times \frac{V_5 - V_6 + V_7 - V_8}{V_5 + V_6 + V_7 + V_8}$$

where G is the gain factor used to discretize interaction positions. By default, we set G = 0.78125, and the corresponding 512 × 512 pixelated space was used to store and display the original scatterplot.

Because responses to scintillation photons varied among different crystals and positions, the original scatterplot did not exhibit a standard scattered point array. A connection between the initial scatterplots and the pixel coordinates of the crystal arrays was established through the following procedure. The original scatterplot underwent image processing (e.g., enhancement, denoising, and smoothing) to identify and mark the most representative positions of different scatters with crystal indices. A Voronoi diagram was then created with these selected positions as seed points, based on the principle of minimum distance between position seeds and every point in the scatterplot [28]. Using this diagram, a lookup table (LUT) mapping photon event decoded positions to corresponding crystal indices was constructed. Through the LUT, the interaction positions of gamma photons were efficiently determined. In this study, we used the center coordinates of the crystal pixel to represent the spatial position where the gamma photon interacted with the detectors for optimal estimation. Thus, the lateral position resolution was 5 mm, and the maximum deviation in the depth direction was 2.5 mm and 5 mm for the scatterer and absorber, respectively.

The next step involved obtaining the energy responses of different crystals. The sum of voltage signals across all layers determined the channel address in the energy spectrum. Each crystal unit required calibration using the following formula:

$$E_{i,j} = a_j \times \left(\sum_{k=1}^{4} V_k\right)^2 + b_j \times \sum_{k=1}^{4} V_k + c_j$$

where $E_{i,j}$ represents the deposited energy in the ith pixel of the jth layer, and a_j, b_j, c_j are calibration parameters. Three types of natural radioactive sources (^{22}Na, ^{57}Co, and ^{137}Cs) with four characteristic energies were used for energy calibration.

For every two-point event, the output list-mode data format was $(x_s, y_s, z_s, E_s, x_a, y_a, z_a, E_a)$. Here, (x_s, y_s) represented the interaction position in the scatterer, with (x_s, y_s) being the lateral position determined by the crystal pixel to which the event was clustered. z_s and z_a represented positions in the depth direction, set as constants (0 mm for the scatterer and -50 mm for the absorber). E_s and E_a represented the deposited energies in the scatterer and absorber, respectively, calculated via Equation (5).

Figure 3 [Figure 3: see original paper]. Framework of the list-mode projection data acquisition for the prototype.

As the developed prototype is expected to detect sources emitting photons of different energies, event selection methods are employed in projection data acquisition to obtain valid events for reconstruction. In our study, the characteristic energy window depended on prior knowledge, or the measured energy spectrum was used to select events with specific total deposited energies for corresponding radioactive sources. Additionally, if only source localization and relative activity reconstruction were required, a broad energy window covering all characteristic energies while eliminating noise could be used, because the CC could reconstruct locations and activities of sources where photons with different energies contribute equally in the back-projected Compton cone formula.

2.3 Reconstruction Algorithm

In this study, the previously proposed SD-OE-RR algorithm was used for reconstruction [3]. This algorithm is an optimized origin ensemble (OE) algorithm developed for CC reconstruction in a large FOV with a projected coordinate system (, ϕ, z) during nuclear decommissioning source term investigation, and it can also evaluate the angular resolution of the proposed $LaBr_3$ CC prototype. The OE algorithm has been proven to yield the same estimate as the MLEM algorithm under certain approximations [29]; however, OE algorithms achieve reconstruction speeds several orders of magnitude faster than MLEM algorithms [26].

OE algorithms utilize transitions between different states as the iterative process. In a typical gamma-ray localization scenario, a detector with K bins receives I events from an image volume divided into J voxels. States can be defined as the locations of I events assigned to J voxels individually; in this case, there are J^I possible states. The reconstruction process seeks the most probable state.

The probability of a particular state s was defined as the product of probabilities of events emitting in specific voxels:

$$P(s) = \prod_{i=1}^{I} p_{i,j_s(i)}$$

where $P(s)$ represents the probability of state s, and $p_{i,j_s(i)}$ represents the probability that the origin of event i is located in voxel j (while event i was considered to be in voxel j in state s). This can be defined as:

$$p_{i,j_s(i)} = \sum_{k=1}^{K} p_{i,j,k} \times \frac{c_j(s)}{\epsilon_j}$$

where $p_{i,j,k}$ represents the probability that event i detected in bin k emits in voxel j, which is the differential cross-section of the current scattering angle calculated via the Klein–Nishina formula in the CC system. $c_j(s)$ represents the number of events whose origin is in voxel j in state s, and ϵ_j represents the sensitivity of voxel j to the detector.

Thus, $c_j(s)/\epsilon_j$ is the estimate of the activity of voxel j in state s. In this case, Equation (6) can be rewritten as:

$$P(s) = \prod_{i=1}^{I} \sum_{k=1}^{K} p_{i,j_s(i),k} \times \frac{c_{j_s(i)}(s)}{\epsilon_{j_s(i)}}$$

Because $c_{j_s(i)}(s)$ is the sum of events thought to emit in voxel j, for calculating $P(s)$, the activity of voxel j is multiplied $c_{j_s(i)}(s)$ times. Equation (8) can thus be rewritten as:

$$P(s) = \prod_{j=1}^{J} \left(\frac{c_j(s)}{\epsilon_j} \right)^{c_j(s)} \times \prod_{i=1}^{I} \sum_{k=1}^{K} p_{i,j_s(i),k}$$

A higher $P(s)$ indicates that the state is closer to the optimal estimate; thus, the OE algorithm iterates by comparing probabilities of two adjacent states and transforming the current state. Here, "adjacent states" refers to two states differing in the location of only one event. The probability ratio can be simplified as:

$$\frac{P(s')}{P(s)} = \frac{c_{j'}(s')/\epsilon_{j'}}{c_j(s)/\epsilon_j} \times \frac{\sum_{k=1}^{K} p_{i,j',k}}{\sum_{k=1}^{K} p_{i,j,k}}$$

For the CC system, an event only emits on the Compton cone; thus, $\sum_{k=1}^{K} p_{i,j,k}$ is equal to either P_{cone} or 0. In the former case, j' and j are on the same Compton cone, and the sensitivities of all voxels are approximately equal for far-field reconstruction. In the latter case, voxel j' is not on the Compton cone. Thus, these terms can be canceled.

Additionally, the following approximation can be made when $c_j \gg 1$:

$$\frac{c_{j'}(s')/\epsilon_{j'}}{c_j(s)/\epsilon_j} \approx \frac{c_{j'}(s) + 1}{c_j(s)}$$

The probability ratio can therefore be simplified as:

$$\frac{P(s')}{P(s)} \approx \frac{c_{j'}(s) + 1}{c_j(s)}$$

Usually, the initial activity estimate has no restrictions, but a more accurate initial state leads to higher convergence rates and better reconstruction results. In the OE algorithm, events are stochastically assigned to voxels on the corresponding Compton cone as an initial state. However, due to finite energy resolution, position resolution, and the Doppler broadening effect, the Compton cone calculated from list-mode data cannot cover all possible voxels where events may have originated. The SD-OE-RR algorithm accounts for these effects on angular resolution.

The influence of energy resolution and the Doppler effect on the deviation of the calculated scattering angle can be expressed as follows [3]:

$$\Delta(\cos\theta)_E = \cos\theta \cdot \frac{(1+\cos^2\theta)}{E_s} \cdot \sqrt{2\Delta E_s^2 + \Delta E_d^2 + \Delta E_{dopp}^2}$$

where E_s represents the deposited energy in the scatterer, ΔE_s and ΔE_d represent the statistical fluctuations in deposited energy in the scatterer and absorber, respectively, and ΔE_{dopp} represents the energy deviation caused by the Doppler broadening effect. E_e represents the static energy of the electron.

For position resolution, the effects of interaction position deviation on scattering angle deviation can be expressed as [30]:

$$\Delta(\cos\theta)_r = \frac{(1+\cos\theta)}{|r_{s,i}|} \cdot \left(\frac{\Delta r_s \cdot \sin\theta_s}{|r_{s,i}|} + \frac{\Delta r_a \cdot \sin\theta_a}{|r_{a,i}|}\right)$$

where $r_{s,i}$ is a vector from the voxel in the FOV to the interaction position in the scatterer, and $r_{a,i}$ is a vector from the interaction position in the scatterer to the interaction position in the absorber for the ith event. θ represents the scattering angle determined by deposited energies in the scatterer and absorber. Δr_{lat} represents the lateral position resolution, while Δr_s and Δr_a represent position resolutions along the depth directions of the scatterer and absorber, respectively. k represents the ratio of the distance between the source and interaction position in the scatterer to the distance between interaction positions in the scatterer and absorber, i.e., $k = |r_{s,i}|/|r_{a,i}|$.

The total deviation of the scattering angle is the geometric mean of the aforementioned effects:

$$\Delta\cos\theta_i = \sqrt{\Delta(\cos\theta)_E^2 + \Delta(\cos\theta)_r^2}$$

In contrast to the OE algorithm, the SD-OE-RR algorithm stores all voxel indices (subsets of the OEs) by traversing all possible voxels for photon events with cones and deviations via Equation (15). $\Delta(\cos\theta)$ was 0.06 for the fabricated $LaBr_3$ CC prototype, as calculated by Equations (12)–(14).

After a back-projection process with equal weighting of 1, the initial estimate of the activity distribution considering resolution effects can be obtained as:

$$\lambda_j^{(0)} = \sum_{i=1}^{I} \frac{1}{\Delta \cos \theta_i} \cdot \delta(j \in S_i)$$

The iterative process of the SD-OE-RR algorithm is given by Equations (17) and (18):

$$c_j^{(n+1)} = \max\{\mathrm{sgn}(c_j^{(n)} - c_{j'}^{(n)}) \cdot \mathrm{sgn}(c_j^{(n)} + 1) \cdot (c_j^{(n)} + 1), \mathrm{sgn}(c_{j'}^{(n)} - c_j^{(n)}) \cdot \mathrm{sgn}(c_j^{(n)}) \cdot (c_j^{(n)} - 1)\}$$

$$c_{j'}^{(n+1)} = \max\{\mathrm{sgn}(c_j^{(n)} - c_{j'}^{(n)}) \cdot \mathrm{sgn}(c_{j'}^{(n)} + 1) \cdot (c_{j'}^{(n)} - 1), \mathrm{sgn}(c_{j'}^{(n)} - c_j^{(n)}) \cdot \mathrm{sgn}(c_{j'}^{(n)}) \cdot (c_{j'}^{(n)} + 1)\}$$

where $c_j^{(n)}$ represents the count in voxel j in the nth iteration, and j, j' represent the positions of event i in the current state and proposed new state, respectively. α is a random number in the range 0–1 used in the (n+1)th iteration. sgn(x) denotes the signum function, which equals −1 when x < 0 and 1 when x > 0. The implementation steps are presented below [31].

Step 1: Calculate the deviations of all photon event cones using Equation (14) with position and energy uncertainties and the Doppler broadening effect.

Step 2: Use $\Delta(\cos\theta)$ in Equation (15) to obtain the subsets of OEs for event i.

Step 3: Use the sum of all initial event counts of voxels in S_i as an initial estimate of the source distribution.

Step 4: Randomly select one event i. Randomly select a new location (i.e., voxel j') for this event in the ith row vector of S_i for state s'. Obtain the corresponding event counts of the voxel where event i is located for states s and s', respectively.

Step 5: Determine the acceptance probability A for the new location of event i using Equation (16) and generate a random number α uniformly distributed between 0 and 1. Event i moves to the new location if $A > \alpha$ and remains at the current location if $A \leq \alpha$. The voxel where event i is located after this operation becomes the old location for the next iteration, and the corresponding event counts of voxels in S_i are updated.

Step 6: Repeating Steps 2–4 N times corresponds to one full iteration of the algorithm. After a sufficient number of iterations (3×10^6), the event counts in the voxels become approximately invariant, and the reconstructed image is obtained by summing all weights of the same voxel in the sparse matrix.

2.4 Monte Carlo Simulation

Geant4 p10.03 was used to model the CC with the same structure, position resolution, and energy resolution as the fabricated prototype. The Doppler broadening effect was included in the simulations. Four simulation scenarios were conducted to evaluate the angular resolution of the CC under different conditions: varying angles, distances, source areas, and source energies.

1. **Angular resolution with different angles:** An ideal point-like source was placed at 25 positions along lateral and diagonal directions in the FOV. The distance between the source and the CC scatterer was 10 cm.
2. **Angular resolution with different distances:** An ideal point-like source was placed at the center of the FOV, and the distance between the source and the CC scatterer was varied from 5 cm to 1 m.
3. **Angular resolution of sources with different areas:** Circular plane sources with radii varying from 0.5 to 5 cm were placed at the center of the FOV, with the source-to-scatterer distance fixed at 10 cm.
4. **Angular resolution of sources with different energies:** An ideal point-like source was placed at the center of the FOV. Source energies were set to 511, 662, and 1275 keV for single-energy simulations. For multiple-energy sources, energies were set as combinations of two of the aforementioned three energies, each accounting for 50%. An additional combination of 64.3% 511 keV and 35.7% 1275 keV was used to simulate a real ^{22}Na source. The source-to-scatterer distance was 5 cm. Because variations caused by energy deviation were relatively small, a short distance amplified these variations and made them more perceptible.

Approximately 10,000 events were used for reconstruction in each simulation. The projection data obtained from simulations incorporated the position resolution and energy resolution of the CC (consistent with the fabricated prototype) as well as the Doppler broadening effect. Lateral event positions were shifted to the center coordinates of the nearest pixels. Depth positions were set to 0 mm or −50 mm for the scatterer and absorber, respectively. Deposited energy was degraded by Gaussian noise representing uncertainties from the Doppler broadening effect and energy resolution. As both noise and simulation data were stochastic, results were averaged over five reconstructions under identical conditions.

Angular resolution was defined in a plane coordinate system as follows [32]:

$$\mathrm{FWHM}_\theta = \arctan\left(\frac{\mathrm{FWHM}_o}{d}\right)$$

where FWHM_o represents the mean value of full widths at half maximum (FWHMs) in profiles taken from different angles through the source, and d represents the distance between the source and the scatterer. For the projected coordinate system used in this study, this transformed to:

$$\mathrm{FWHM}_\theta = \arctan\left(\frac{\mathrm{FWHM}_a}{d}\right)$$

where FWHM_a has a similar definition to FWHM_o but is measured in projected coordinates with units of degrees, and represents the angle between the Z-axis and the line passing through the source and the center of the scatterer. For convenience, FWHM_θ is used to represent angular resolution hereinafter, with units of degrees.

Figure 4 [Figure 4: see original paper]. (a) Setup of the $LaBr_3$ CC in the simulation. (b) Schematic of simulated ideal point-like sources in the FOV.

2.5 Experiments

In the experiments, a point-like ^{137}Cs source with an activity of approximately 9000 Bq was placed at three positions matching those used in the simulations. The distance between the source and the prototype scatterer was 5 cm. Each measurement lasted 5 minutes. The numbers of obtained coincident events with total energy in the 600–700 keV range were 315, 360, and 205, respectively.

Figure 5 [Figure 5: see original paper]. ^{137}Cs point-like source imaging experiments with the $LaBr_3$ CC prototype at three positions.

3.1 Position Decoding and Energy Spectrum Calibration

The scatterplots of the scatterer and absorber constructed from detection results of the ^{22}Na source are shown in Figure 6 [Figure 6: see original paper]. An LUT was created after numbering all centroids, providing a fast clustering method. Distances between all pixel points in the scatterplots and every centroid of the point group were compared, and each pixel was labeled with the number of the nearest centroid. Voronoi diagrams for each layer are shown in Figures 6(c) and (d). In these diagrams, the scatterplots are segmented by white lines, indicating that any event decoded within a single area would be clustered to the corresponding crystal pixel. The final decoded interaction positions of all events are also shown in Figure 6.

To obtain the total energy response of the scatterer and absorber, the energy response of every crystal was measured and calibrated. ^{22}Na, ^{57}Co, and ^{137}Cs sources with characteristic energies of 122, 511, 662, and 1275 keV were used for calibration. Figure 7 [Figure 7: see original paper] shows the energy responses of a corner pixel, an edge pixel, and a center pixel to the ^{22}Na source. The calibration result for the central pixel is also shown as a typical example. The energy resolution of each layer was evaluated using the total energy spectrum obtained from all pixels.

The mean energy resolution of the scatterer was 20.63% at 122 keV, 7.64% at 511 keV, 6.34% at 662 keV, and 4.64% at 1275 keV. The mean energy resolution of the absorber was 24.12% at 122 keV, 8.44% at 511 keV, 7.99% at 662 keV, and 5.97% at 1275 keV. The energy resolution trend was fitted by:

$$\mathrm{ER}_j(E) = \frac{p_j}{\sqrt{E}} + q_j$$

where j denotes the jth layer. The results in Figure 8 [Figure 8: see original paper] indicate that p_j was 2.727 for the scatterer (j = 1) and 3.020 for the absorber (j = 2), while q_j was –0.0345 for the scatterer (j = 1) and –0.0359 for the absorber (j = 2). For the characteristic energy of ^{60}Co (1.33 MeV), the expected energy resolution was 4% and 5% for the scatterer and absorber, respectively. For a typical high energy of 4.44 MeV used in hadron therapy based on ^{12}C de-excitation, the expected energy resolution was approximately 1% for both layers.

Figure 6. (a, b) Initial scatterplots of the scatterer and absorber from ^{22}Na obtained using decoding Equations (1)–(4). (c, d) Voronoi diagram of each layer. (e, f) Corresponding decoded interaction positions.

Figure 7. Partial results of single-pixel energy spectra of ^{22}Na: (a–c) corner, edge, and center pixels of the scatterer, respectively; (d–f) corner, edge, and center pixels of the absorber, respectively.

Figure 8. Spectral performance of the scatterer and absorber measured using the prototype at four energies (122, 511, 662, and 1275 keV) of ^{22}Na, ^{137}Cs, and ^{57}Co: (a) linear relationship between energies and channels; (b) measured energy resolutions and fitting curves.

3.2 Simulations

As shown in Figures 9 and 10, the CC distinguished and accurately reconstructed the spatial positions of radioactive sources. The angular resolution was approximately 5.5° in the region near the center of the FOV but degraded to approximately 8° at the edge. The proposed CC demonstrated good performance with uniform and high angular resolution in the region of –50° to 50°. Figure 11 [Figure 11: see original paper] shows reconstruction results for the point-like source at three characteristic positions, which were compared with prototype experimental results.

Table 1 presents the trend of angular resolution with respect to distance between the source and scatterer. The FWHM decreased as distance increased, but the downward trend stabilized. **Tables 2 and 3** present angular resolutions for circular plane sources of different radii and point sources of different energies, respectively. As source radius increased, FWHM increased. Meanwhile, FWHM decreased as energy increased for both single-energy and multiple-energy sources.

Figure 9 [Figure 9: see original paper]. Reconstruction results with the point-like source placed at different lateral positions in simulations: (a) joint two-dimensional images; (b) profiles along the x-axis; (c) FWHMs at corresponding positions.

Figure 10 [Figure 10: see original paper]. Reconstruction results with the point-like source placed at different positions along the diagonal of the FOV in simulations: (a) joint two-dimensional images; (b) profiles along the diagonal line; (c) FWHMs at corresponding positions.

Figure 11. Reconstruction results for the point-like source at three positions in simulations.

Table 1. FWHMs (degrees) for reconstructed radioactive source (^{137}Cs) at different distances (cm).

Distance	FWHM
5 cm	5.5°
10 cm	4.2°
20 cm	3.8°
50 cm	3.5°
100 cm	3.4°

Table 2 . FWHMs (degrees) for reconstructed radioactive sources (^{137}Cs) of different radii (cm).

Radius	FWHM
0.5 cm	5.8°
1.0 cm	6.2°
2.0 cm	7.1°
3.0 cm	8.0°
5.0 cm	10.2°

Table 3 . FWHMs (degrees) for reconstructed radioactive sources of different energies (keV) at 5 cm.

Energy Configuration	FWHM
511 keV (single)	6.1°
662 keV (single)	5.5°
1275 keV (single)	4.8°
50% 511 + 50% 662	5.7°
50% 662 + 50% 1275	5.1°
50% 511 + 50% 1275	5.3°

Energy Configuration	FWHM
64.3% 511 + 35.7% 1275 (^{22}Na)	5.4°

3.3 Experiments

As shown in Figure 12 [Figure 12: see original paper], reconstruction results obtained using the $LaBr_3$ CC were consistent with simulation results. **Table 4** indicates that deviations between reconstruction positions and exact values in the three experiments were <1.5°. Additionally, as shown in **Table 5** , FWHMs of the reconstructed radioactive source at three different positions in the ^{137}Cs point-like source experiments agreed well with corresponding simulation results.

Preliminary experimental results indicated an angular resolution of approximately 6°. However, limited by the activity of the ^{137}Cs source and measurement time, the number of coincidence events obtained was only several hundred. Consequently, reconstruction images contained relatively large amounts of noise and artifacts due to limited projection data [33]. As shown in the rightmost frame of Figure 12, which presents the source placed at the edge position, sensitivity was lower than at the center of the FOV, resulting in the smallest number of detected events among the three positions. Deviation in projection data, including interaction positions and deposited energies, combined with limited statistics, led to reconstruction with more significant artifacts compared with the other two positions.

Figure 12. Reconstruction results for the ^{137}Cs point-like source with the fabricated $LaBr_3$ CC prototype at three positions.

Table 4. Deviations (degrees) between reconstruction positions and exact values in experiments.

Position	Exact (x, y)	Reconstruction (x, y)	Deviation
1	(-25, 0)	(-24.09, -1.42)	1.4°
2	(0, 0)	(-1.42, 0.47)	1.5°
3	(15, -15)	(15.59, 13.70)	1.2°

Table 5 . FWHMs (degrees) of reconstructed radioactive source at three positions for MC simulations and prototype experiments (from Figures 11 and 12).

Position	Simulation	Experiment
Center	5.5°	6.0°
Edge 1	6.2°	6.8°
Edge 2	7.8°	8.1°

4. Discussion

In this study, we designed and developed a two-layer $LaBr_3$-based CC with large pixel size and evaluated its performance through MC simulations and experiments. We employed an LUT to acquire list-mode data and the SD-OE-RR algorithm to reconstruct images, thereby assessing the feasibility of the CC prototype.

To spatially cluster energy-depositing events within crystal units, Voronoi diagrams and LUTs were created. For each layer, 4-channel voltage signals representing scintillation photon counts were output in each time window, and the Anger camera method was used to decode these 4-channel data. We then created scatterplots of energy-depositing events. The centroids of crystal units were selected as interaction positions for events decoded in corresponding scatterplot areas to achieve optimal estimation. Voronoi diagrams and LUTs were created for event clustering. In the Voronoi diagrams, the distance from any point in each segmented region to its seed point is the shortest among distances to all seed points—this principle guided our event clustering approach. We selected the most representative points among bright spots by identifying peaks in processed scatterplots and created Voronoi diagrams for both scatterer and absorber. LUTs were then constructed accordingly.

However, this complex process was based on nonstandard scatterplots due to hardware and structural limitations. We used light-absorbing material around the $LaBr_3$ crystal to differentiate energy responses of edge pixels, resulting in relatively low-voltage signals with high noise in edge pixels (as shown in Figure 7). Resistances in the encoding circuit had deviations of approximately 1%, introducing spatial errors in the decoding process. Another limitation was incomplete correction for baseline drift in encoding circuits, causing approximately 200-channel deviations in voltage signals that affected both position and energy decoding.

The detection efficiency of the prototype for the ^{137}Cs source used in our experiments was 1.67×10^{-3} at 662 keV. Compared with the $LaBr_3$-based CC developed by the IRIS group (MACACO), our prototype's energy resolution was slightly lower, likely due to system defects. Because $LaBr_3$ crystals are hygroscopic, we used a 1-mm-thick glass plate and a 1.2-mm-thick Al shell for vacuum packaging of each layer. The glass plate behind the crystal absorbed some scintillation photons, and the Al shell surrounding the crystal caused Compton scattering of gamma photons; both effects led to incorrect deposited energy values and reduced energy resolution.

Additionally, minor background radiation from ^{138}La could influence energy resolution [23, 34]. However, the natural abundance of ^{138}La is only approximately 0.09% with a long half-life, making its background radiation influence negligible. Furthermore, the overall energy resolution of our prototype represented the average across all detector pixels. The energy response of edge pixels reduced the overall energy resolution due to our prototype's structure, as previously mentioned. As shown in Figure 13 [Figure 13: see original paper], the best energy resolution of $LaBr_3$ pixels in our CC was approximately 5% for 511-keV gamma rays, while the worst was approximately 15%. Thus, the overall energy resolution of our $LaBr_3$ CC is worse than that achieved in a previous $LaBr_3$ scintillator detector experiment (approximately 4%) [35] but comparable to simulation results under similar conditions [22]. Another comparable system—MACACO, a similar $LaBr_3$-based CC employing a monolithic $LaBr_3$ crystal and 3-mm^2 SiPM array—achieved an angular resolution of approximately 5°, better than our CC due to structural advantages but worse than ideal experimental values because its mutual decoding mode prevented optimal performance. Although energy resolution was affected by these system defects, our CC still achieved good energy resolution and is expected to enable accurate nuclear material waste detection. Furthermore, using SiPMs larger than the scintillator array or implementing one-to-one correspondence between SiPMs and crystal arrays could reduce scintillation photon loss and improve energy response of edge pixels.

Reconstruction simulation results indicated that our CC's angular resolution improved when sources were moved away from the FOV center, suggesting that larger scattering angles correspond to better resolution [36]. As source-to-scatterer distance increased, angular resolution improved, consistent with previous studies [32]. Two factors may explain this phenomenon. First, scattering angle deviation decreased with increasing distance, as described by Equation (13). Second, the system better satisfied far-field conditions, improving resolution. Additionally, point source angular resolution improved slightly with increasing energy due to better energy resolution at higher energies. Imaging performance for multiple-energy sources exhibited similar trends to single-energy sources, and excellent simulation results for a real point-like ^{22}Na source (64.3% 511 keV and 35.7% 1275 keV) demonstrated the developed CC's applicability to nuclear decommissioning. Angular resolution for circular plane sources worsened as radii increased.

For the point-like ^{137}Cs source, experimental reconstruction results agreed well with simulation results, as shown in Table 2. The average FWHM of reconstructed sources was approximately 6° in experiments and 5.5° in simulations. Additionally, reconstruction positions showed small deviations. Prototype imaging results indicated that under our experimental conditions, high energy resolution led to good imaging performance despite low spatial resolution from large pixel size.

Compared with a previously reported LYSO CC prototype using the same reconstruction algorithm, our $LaBr_3$ CC performance was significantly better, even though the LYSO detectors had a small pixel size of 1 mm [17]. Similarly, in Dennis et al.'s study, energy resolution effects on performance were more pronounced than spatial resolution effects for detected gamma energies <2 MeV [37]. The same trend was derived through theoretical analysis using Equations (12) and (13). In our system, the radioactive source had low energy (662 keV)—close to the electron static energy—which made the energy resolution term have a larger impact on total deviation. Thus, when the CC is used for radioactive material detection, improving energy response may be more effective for enhancing imaging performance than improving geometric structure. With high detector energy resolution, relatively loose geometric restrictions can be tolerated to achieve better sensitivity, provided the CC system exhibits sufficient imaging performance for intended applications.

We investigated other large-pixel CCs, such as a GAGG CC used in Fukushima for radioactive material detection [18, 19] and a CZT CC [38]. The GAGG CC had similar geometric parameters to ours but produced significantly worse results, primarily due to poor GAGG scintillator energy resolution. In contrast, MLEM reconstruction results from the CZT CC, which had even larger pixel sizes than our CC, were comparable to our experimental results. This first practical verification demonstrates that the two-layer $LaBr_3$-based CC with large pixel size developed in this study achieves high angular resolution and good reconstruction performance, making it promising for radioactive source positioning in nuclear industry applications (e.g., nuclear decommissioning). Although detection efficiency is relatively low, our prototype indicates that thicker crystal arrays can be used in future CCs, and $LaBr_3$-based CCs are also expected to find application in nuclear medical imaging.

Future research will further evaluate our prototype's performance in actual usage scenarios through more detailed experiments and simulations, focusing on applications in nuclear decommissioning, natural radioactive background monitoring, and nuclear medical imaging. We will also optimize our CC structure (e.g., improving packaging methods and reducing pixel size) to enhance prototype performance. Improved techniques for locating interaction positions are also under consideration. Bilayer SiPMs could be employed in each layer to obtain not only lateral position but also more accurate depth information for events.

5. Conclusion

We developed a two-layer $LaBr_3$-based CC prototype with large pixel size, along with a highly efficient technique for determining interaction positions by decoding 4-channel voltage signals and performing clustering using Voronoi diagram-based LUTs. Based on calibration of each crystal pixel's energy response, we established a framework for obtaining list-mode data from two-point events. Experimental and simulation results indicated that the developed CC prototype achieved an angular resolution of approximately 6° for a ^{137}Cs point-like source at 5 cm and a detection efficiency of 1.67×10^{-3}. The imaging performance of the developed prototype satisfies requirements for radioactive source positioning in nuclear industry applications and nuclear medicine.

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Note: Figure translations are in progress. See original paper for figures.