Energy response correction for imaging detectors based on monolithic crystals

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Date: 2025-07-03T00:00:00+00:00

Abstract

The energy response of an imaging detector based on a monolithic crystal is highly dependent on the position of the gamma ray interaction, which leads to a spectral drift of the imaging detector, known as the spectral drift related to incident position. It deteriorates the energy resolution of the detector and affects the selection of the energy window for imaging, resulting in artefacts in the reconstructed image. Thus, a energy response correction method is proposed to improve the positional consistency of the detector energy response. In both simulation and physical experiments, the method improved the full-energy peak consistency of the monolithic crystal detector, which results in improved energy resolution of the detector, more accurate selection of the energy window, and imaging quality. Especially, in physical experiments, the method converges the peak sites of 365keV energy at each location, which reduced the half-height width of characteristic peak (@365 keV) from 53 to 38 channels, improved the energy resolution by 28.3%, transformed the incomplete mask projection into a complete mask projection, and the signal-to-noise ratio increased from 2.38 to 5.37.

Full Text

Preamble

Energy Response Correction for Imaging Detectors Based on Monolithic Crystals

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The energy response of imaging detectors based on monolithic crystals exhibits strong dependence on the position of gamma-ray interaction, leading to spectral

drift that varies with incident position. This phenomenon degrades detector energy resolution and complicates energy window selection for imaging, ultimately producing artifacts in reconstructed images. To address this, we propose an energy response correction method that improves the positional consistency of detector energy response. Both simulation and physical experiments demonstrate that this method enhances full-energy peak consistency in monolithic crystal detectors, resulting in improved energy resolution, more accurate energy window selection, and enhanced imaging quality. Notably, in physical experiments, the corrected peaks converge to 365 keV across all positions, reducing the full width at half maximum (FWHM) of the characteristic peak (@365 keV) from 53 to 38 channels and improving energy resolution by 28.3%. Furthermore, the method transforms incomplete mask projections into complete ones, increasing the signal-to-noise ratio from 2.38 to 5.37.

Keywords: Monolithic crystal detector, SiPM array, Spectral drift, Energy response correction method

Introduction

Gamma-ray imaging systems, which excel at monitoring the spatial distribution of radioactive materials, have become essential tools in nuclear radiation monitoring and national nuclear emergency response applications [1–5]. Among these systems, coded aperture imaging technology stands out for its high imaging sensitivity and superior signal-to-noise ratio, leading to widespread adoption across various nuclear facilities for safety applications [6–9]. Consequently, performance demands on coded aperture imaging technology continue to increase [10–13].

Two primary types of scintillator crystals are employed in coded aperture imaging: pixelated array crystals and monolithic crystals. Imaging detectors using array crystals suffer less from compression effects and can achieve higher spatial resolution, which is fundamentally limited by the pixel size of the crystal array [14–16]. However, these detectors exhibit significant drawbacks: photon absorption by reflective layer material between crystal pixels and the inherent thickness of crystal arrays substantially reduce both energy resolution and detection efficiency [17]. Moreover, in imaging detectors composed of array crystals coupled to photomultiplier tubes or silicon photomultiplier tubes, spectral peaks vary considerably among individual crystal strips [18–20].

In contrast, monolithic crystals offer superior energy resolution and detection efficiency compared to array detectors [17]. Nevertheless, the energy response of monolithic crystals can be inconsistent due to variations in incident gamma-ray position [21]. This inconsistency becomes more pronounced when the detector surface is covered with absorbing material, as photons are absorbed non-uniformly [22, 23]. In positron emission tomography (PET), inconsistent energy responses arise from different interaction depths of radiation. Correcting the pulse signal amplitude for 511 keV gamma rays in PET has successfully improved energy resolution [24–26]. Our imaging experiments have revealed that thin monolithic crystals can exhibit non-uniform energy responses due to intrinsic non-uniformities in the crystal itself and variations in packaging, resulting in compromised imaging quality. In previous research, we developed a coded aperture imaging system model based on a monolithic $LaBr_3$(Ce) crystal [17, 27].

This study investigates the impact of energy response inconsistencies on coded aperture imaging systems through Monte Carlo simulations and physical experiments. Using a step-scanning method, we obtained an energy response correction model that enhances peak consistency, improves energy resolution, and sharpens imaging quality. These findings are significant for optimizing coded aperture imaging system performance and improving the quality of nuclear radiation monitoring.

2. Materials and Methods

We established an imaging detector model using GEANT4 and employed a step-scanning method to characterize spectral drift related to incident position. Additionally, we built a radiation imaging system based on this model, incorporating electronic and data processing subsystems. Following the simulation experimental methodology, we confirmed that spectral drift related to incident position also occurs in physical experiments, where the effect is even more severe.

2.1. Simulation

To investigate spectral drift related to incident position, we constructed a monolithic scintillator-based imaging detector model using GEANT4 software. The model employs a monolithic $LaBr_3$(Ce) crystal, chosen for its exceptional properties including high density, excellent energy resolution, high light yield, and fast decay time. [Figure 1: see original paper] illustrates the detector structure and step-scanning process.

The detector model consists of a 51 mm × 51 mm × 5 mm $LaBr_3$(Ce) crystal coated with a 0.3 mm Teflon foil serving as the front diffuse reflective layer. The scintillator is surrounded and encapsulated by a 0.5 mm aluminum foil acting as the specular reflective layer [17]. A glass layer (3 mm thickness, refractive index 1.5) and optical grease (0.1 mm thickness, refractive index 1.41) are placed between the crystal bottom and the silicon photomultiplier (SiPM) array. The SiPM used in the model is the Micro-30035-TSV model manufactured by ON-SEMI, featuring a 16 × 16 array with a sensitive area of 3.07 mm × 3.07 mm and a package area of 3.15 mm × 3.15 mm [17].

The physical property parameters of lanthanum bromide crystals include the emission spectrum, light yield, decay time constant, refractive index, and intrinsic resolution. The emission spectrum of $LaBr_3$(Ce) crystals varies with Ce content. As Ce concentration increases, light yield changes slightly while decay time decreases. Typically, the decay time constant comprises both fast and slow components. Since the fast decay component of $LaBr_3$:5% Ce crystals accounts for 97% of the total, we modeled only the fast component, setting it to 15 ns with a yield value of 1 [28, 29]. The crystal' s light yield (scintillation yield, SCY) is set to 63,000 photons/MeV, and the refractive index is set to 1.85 [29]. In GEANT4, the emission spectrum obtained from physical experiments [30] is used to establish the crystal model' s emission spectrum. A distinctive feature of lanthanum bromide crystals is the presence of radioactive materials ^{138}La and ^{227}Ac within the crystal lattice. These radionuclides endow $LaBr_3$(Ce) crystals with intrinsic radioactivity, producing a background energy spectrum that differs slightly from the natural background spectrum. In the low-energy region (0–1800 keV), the background spectrum is dominated by gamma transitions from ^{138}La (789 keV–1436 keV). When simulating the background spectrum, we calculate the total activity of ^{138}La based on detector crystal volume and randomly distribute it throughout the crystal (the volumetric activity of ^{138}La is 1.52 Bq/cm^3) [31, 32], yielding a total activity of 19.7 Bq. Due to the crystal' s small size, its absorption capacity for 789 keV and 1436 keV gamma rays is limited, minimally impacting imaging results. In the high-energy region (1800 keV–2800 keV), radiation primarily originates from ^{227}Ac and high-energy environmental background radiation. Since the total count of high-energy rays is small, their impact on energy spectrum measurement and imaging results is negligible.

In the simulation study, to accurately model optical photon transport, we incorporated both the transport of optical photons within the medium and transport across different media [33–35].

The effective detection area of the monolithic crystal imaging detector is artificially divided into 441 blocks. A point source is simulated using the Class PrimaryGeneratorAction, positioned 180 mm in front of the imaging detector to define emission position and direction. An I-131 radioactive source is placed within a tungsten shielding canister on the detector' s incident side. The tungsten shielding canister includes a collimation hole, allowing γ-rays from I-131 to impinge perpendicularly on the detector. Using a step-scanning method, each block is scanned to obtain the detector response for all ray entry positions. When gamma rays enter the detector from a specific block and interact with the scintillator to produce photons, these photons are converted into electrical signals by the SiPM array. Signals from all 256 SiPMs are summed to serve as the detector' s energy response. The summed SiPM array signal is then statistically processed to obtain the γ-ray spectrum for each incident block, from which the peak channel of each gamma-ray spectrum is extracted. Since events occurring near the crystal center produce relatively complete light distributions, while gamma-ray interactions at the crystal edge result in truncated light distributions, we use the peak channel from Block (00,00) as the standard reference.

In simulation experiments, we obtained gamma-ray energy spectra across various detector blocks for ten common energies. Ten distinct spectral peaks are clearly visible in these spectra, confirming the feasibility of our model [27]. We isolated the characteristic peak at 365 keV, shown in Fig. 1b. Notably, significant spectral drift related to incident position occurs from Block (00,00) to Block (10,10), with the effect becoming more pronounced at higher energies.

2.2. Experiment

[Figure 2: see original paper] shows the radiation imaging system, which primarily consists of an encoding plate (MURA-11), imaging detector, electronic system, Jetson Xavier NX, and display unit. The imaging detector comprises a $LaBr_3$(Ce) crystal coupled to an SiPM array. This work utilizes the ARRAYJ-30035-64P SiPM array model manufactured by Onsemi. Four such arrays are assembled to form a 16 × 16 detector array, producing 256 channels of output signals.

The ARRAYJ-30035-64P consists of 3 mm × 3 mm J-series SiPMs arranged in an 8 × 8 array. Four SiPM arrays are mounted to the front of the interface board via connectors on the back, leaving a 1 mm gap between arrays to facilitate detector packaging. The back of the interface board contains four pairs of connectors for SiPM array bias voltage input and initial signal readout. All sensor substrates (cathodes) are combined to form a common I/O. After completing internal detector packaging, the assembly is secured to the detector housing through mounting holes at the four corners of the interface board. In the interface board design, due to limited copper plating and connector light leakage, black tape is applied for additional light shielding to achieve better optical isolation.

The electronic system comprises a Symmetric Charge Division Circuit (SCDC), Amplitude Time Convert Circuit (ATCC), and Digital Signal Processing Circuit (DSPC). The ATCC initially employs an AD8066 operational amplifier to sum and amplify signals, scaling them to appropriate amplitudes for input into a hysteresis comparator circuit. The comparator uses the TLV350 device, and the hysteresis comparison circuit shapes the nuclear pulse signal into a rectangular pulse signal. The 256-channel signals read from the SiPM array detector are combined into 32-channel signals through a summing circuit and input to the DSPC via an FPC interface for FPGA acquisition. The DSPC incorporates a Xilinx 7 Series core board and system power board. The core board captures the 32-channel rectangular pulse signals output by the conditioning board through its 32 I/O ports. A single channel signal that has undergone A/D conversion is acquired by the FPGA for filtering, shaping, peak extraction, and energy spectrum analysis. The 33-channel signal data (32 rectangular pulse signals and 1 ADC channel) processed by the core board are transmitted via Ethernet to the Jetson Xavier NX for further processing. The Jetson Xavier NX, NVIDIA' s edge computing platform, deploys 32-FCNN localization algorithms and maximum likelihood estimation algorithms (MLEM), enabling parallel computation to accelerate algorithm execution. Ultimately, reconstructed images and radioactive source information are displayed on the monitor.

In physical experiments analogous to simulations, an I-131 source is positioned 180 mm from the detector. A step-scanning method is employed, where radiation is collimated to impinge perpendicularly onto the detector surface. The detector captures energy responses at different incident positions. During step-scanning, a collimator with a 2.5 mm hole diameter, 33 mm overall diameter, and 55 mm thickness is used to collimate gamma rays from I-131. The detector' s effective detection area is gridded into 441 blocks, mirroring the simulation approach. An I-131 source (activity 0.1 mCi) is placed above the collimator, marking the incident position as (x,y). Each point is measured for 4 minutes, and the summed signal V from the SiPM array at position (x,y) is acquired through the multi-channel signal acquisition board. The energy spectrum E at each incident position is then statistically derived from signal V using the host computer, completing a single step-scan measurement. The complete step-scan involves 441 measurement points, requiring 29.4 hours total.

2.3. Correction Method

Preliminary simulation studies extracted peak channels for each full-energy peak across the 300 keV to 2000 keV energy range for various blocks. Since a linear relationship exists between peak channel and peak energy, characteristic peaks in each block should also exhibit linear relationships [27]. Therefore, physical experiments can employ a functional correction matrix to improve full-energy peak consistency, though this matrix must be recalibrated.

We investigated the linear relationship between the full-energy peak of the central Block (00,00) and other blocks through physical experiments. Step-scanning experiments impose specific requirements on radiation source type, activity, and size; the laboratory could only provide I-131 meeting these criteria. Since calibrating the functional correction matrix requires full-energy peaks from two or more energies, we selected the two characteristic peaks of I-131 at 284 keV (branching ratio 6.12%) and 365 keV (branching ratio 81.5%) for matrix calibration. Fig. 3a demonstrates the linear relationship between the 284 keV and 365 keV characteristic peaks of the central Block (00,00) and peripheral blocks (09,08) and (10,10) in physical experiments. The linear relationship between Block (00,00) and Block (10,10) follows $y_{10,10} = 0.98x - 36.29$, with $k_{10,10} = 0.98$ and $b_{10,10} = -36.29$. The relationship between Block (00,00) and Block (09,08) follows $y_{09,08} = 1.02x - 38.71$, with $k_{09,08} = 1.02$ and $b_{09,08} = -38.71$. The functional correction matrix is thus composed of coefficients (k,b) from these linear equations.

A linear parameter fitting line is established between the spectral channel address of Block (i, j) and that of the central Block (00,00), expressed as $y_{,} = k_{,} x + b_{,}$. Here, $y_{,}$ represents the peak channel address for Block (i, j), x indicates the peak channel for the central Block (00,00), $k_{,}$ denotes the slope for Block (i, j), and $b_{,}$ represents the y-intercept for Block (i, j). This yields a functional correction matrix (k(i,j), b(i,j)), as shown in Eq. (1):

$$\left\{\begin{matrix} (k_{-10,10}, b_{-10,10}) & (k_{-10,09}, b_{-10,09}) & \cdots & (k_{-10,-09}, b_{-10,-09}) & (k_{-10,-10}, b_{-10,-10}) \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ (k_{00,00}, b_{00,00}) & \cdots & \cdots & \cdots & \cdots \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ (k_{10,10}, b_{10,10}) & (k_{10,09}, b_{10,09}) & \cdots & (k_{10,-09}, b_{10,-09}) & (k_{10,-10}, b_{10,-10}) \end{matrix}\right\}$$

Based on the functional relationship between incident position and energy discovered in this study, we propose an energy response functional correction matrix to correct energy response and improve full-energy peak consistency. First, a step-scanning method calibrates the detector' s correction matrix by irradiating the detector perpendicularly through a collimator, summing and statistically analyzing response signals from the SiPM array to obtain energy spectra, and extracting full-energy peaks and coordinate information. Using linear functions, we obtain coefficients relating each block' s peak channel to the central block' s peak channel, thereby acquiring the detector' s complete energy response functional correction matrix. Finally, using coordinate information from ray-detector interactions and employing a "look-up table" approach, we identify the corresponding correction coefficients from the energy response functional correction matrix to correct the peak channel for each interaction event at different locations, thereby correcting the entire detector' s energy response, as illustrated in Fig. 3c [Figure 3: see original paper]. In Fig. 3c, E(i,j) represents the uncorrected peak address, (k,b) constitutes the functional correction matrix, and E (i,j) represents the corrected peak address.

This imaging system utilizes a neural network-based ray localization algorithm to obtain positional information [35]. The principle relies on the fact that when rays interact with the detector, the SiPM at the interaction point receives the strongest pulse signal intensity, while signal strength gradually decreases for SiPMs at other locations as scintillation light propagates through the crystal. Therefore, ray positions can be located based on light intensity distribution across the SiPM array. In this system, 256-channel SiPM signals are summed and converted into 32-channel signals, which serve as input data for a fully connected neural network to perform ray localization and obtain positional information. The neural network model structure includes one input layer, two hidden layers, and one output layer. The input layer receives 32-channel signals, while the output layer provides the coordinates (X,Y) of the interaction position between incident rays and the crystal. The ReLU activation function is employed. With this approach, the intrinsic spatial resolution of the radiation imaging system reaches 2.67 mm.

The MURA array can be represented by matrix B , where r denotes the number of rows (or columns) in the matrix, which must be a prime number. B = 1 indicates an open aperture, while B = 0 indicates a closed aperture [36]:

$$b_{ij} = \begin{cases} 1 & \text{if } C_r(i)C_r(j) = 1 \\ 0 & \text{otherwise} \end{cases}$$

where 0 ≤ i ≤ r-1 and

$$C_r(i) = \begin{cases} 1 & \text{if } i = \mod x^2 \text{ for some } x \text{ with } 1 \le x \le r \\ -1 & \text{otherwise} \end{cases}$$

The nested MURA coded aperture structure is derived from the MURA (N × N) by expanding the MURA coded aperture in a centrally symmetric manner to nine times its original size, resulting in the Loop MURA (3N × 3N). Subsequently, a coded aperture of size (2N-1)×(2N-1) at the central position is selected to serve as the Nested MURA [36].

After radiation interacts with the crystal, a neural network localization algorithm acquires the encoded image on the detector.

3. Results and Discussion

We evaluated and discussed correction effects on peak consistency from four perspectives: full-energy peak consistency, energy resolution, encoded image quality, and reconstructed image quality.

3.1. Correction Results

To facilitate comparison between uncorrected and corrected results from both simulation and physical experiments, this study uses characteristic gamma rays from I-131 as the measurement object for both modalities. Correction results are discussed in terms of uncorrected versus corrected peak position consistency, energy resolution, encoded images, and reconstructed image quality.

Given the limited variety of radiation sources available in the laboratory, we isolated spectral channels corresponding to the 365 keV peak from the simulation dataset to enable rigorous comparison with experimental results. This extraction provided the 365 keV peak channel across various blocks for subsequent analysis, as shown in Fig. 4a [Figure 4: see original paper]. The correlation between the 365 keV peak channel and spatial positions reveals minimal displacement at the center, increasing toward the periphery. This indicates a positive correlation between displacement magnitude and proximity to the central axis—peak displacement is smallest at the center and gradually increases toward the edges. This phenomenon arises from gamma-ray interactions with the crystal lattice, causing ionization and excitation of lattice atoms followed by photon emission during de-excitation. Photon interactions with the crystal include absorption, refraction, and reflection processes, with backscattering playing a more significant role in peripheral regions. Additionally, photons traversing the crystal are modulated by crystal structure and physical properties, leading to photon flux attenuation. This results in spatial heterogeneity of the detector' s intrinsic response characteristics and position-dependent energy responses to gamma rays.

Fig. 4b illustrates the distribution of 365 keV characteristic peaks from the experiment. Experimental data closely align with Monte Carlo simulation results. Variation in pulse height channel addresses is notably pronounced due to different radiation incident positions. During gamma-ray interaction with the crystal, ionization and excitation of crystal atoms occur, with photons emitted during de-excitation. These photons may be absorbed, refracted, and reflected by the crystal, with edge positions being more significantly affected by backscattering. Moreover, photon propagation within the crystal is influenced by its structure and physical properties, causing light loss. This results in inconsistent energy responses of monolithic crystal detectors. The overall peak position pattern shows that spectral drift related to incident position is minimal near the center and more severe near peripheral positions, similar to simulation results. In experiments, the degree of peak position offset was more severe, reaching 84 channels. Although SiPMs exhibit some temperature drift, the entire experimental process was conducted at room temperature, with the signal processing circuit board and FPGA chip maintaining essentially constant temperature. Therefore, spectral drift caused by temperature can be considered negligible. This result is attributed to non-uniformity in the actual crystal. In simulations, the $LaBr_3$(Ce) crystal is isotropic with perfectly uniform properties throughout. Real $LaBr_3$(Ce) crystals lack such uniformity, manifesting in specific crystal growth directions and variations in Ce doping concentrations at different locations. These differences cause inhomogeneous anisotropic photon transmission and variations in photon emission during scintillation events of equal energy. These inconsistencies affect detector pulse signal amplitude, thereby influencing energy resolution. Additionally, differences in crystal packaging contribute to this effect. In simulation, not only is the crystal itself perfectly uniform, but the crystal surface packaging is also consistent everywhere—difficult to achieve experimentally. Differences in $LaBr_3$(Ce) surface packaging make the light transmission process non-uniform and asymmetric. When charged particles are incident from different crystal surface positions, geometric factors affect photon transmission, eventually resulting in different peak positions.

Based on full-energy peak consistency analysis, we obtained energy response functional correction matrices separately from simulation and physical calibration experiments. Applying these matrices to correct energy responses in both simulated and physical experiments significantly improved full-energy peak consistency. Fig. 4c shows the corrected 365 keV peak for various incident blocks in simulation, while Fig. 4d presents the experimental results. The figures demonstrate significant correction of peaks in edge blocks for both simulation and experiment, with markedly enhanced full-energy peak consistency essentially converging to uniformity. Additionally, within the 365–1332 keV energy range, simulation results are well-fitted by the energy response functional correction matrix [27]. The energy response functional correction matrix is designed to channel the 284 keV and 365 keV energies of I-131 in the experiment, reducing peak channel error to zero channels in the physical experiment.

Uncorrected peak inconsistencies cause variations in detector energy resolution. When incident gamma rays are predominantly absorbed by edge blocks, detector energy resolution decreases. Conversely, when the central block primarily absorbs incoming rays, energy resolution improves. Thus, enhancing full-energy peak consistency also improves energy resolution. The energy response functional correction matrix obtained from both simulation and experiment corrects energy response, resulting in improved energy resolution. Fig. 4e and Fig. 4f show energy resolution at 365 keV before and after correction for simulation and experiment, respectively. Comparison reveals that corrected gamma-ray spectra exhibit narrowed FWHM, increased peak counts, and improved energy resolution. In simulation, the FWHM of the 365 keV characteristic peak decreased from 38 to 32 channels, improving energy resolution by 18.8%. In experiment, the FWHM decreased from 53 to 38 channels, improving energy resolution by 28.3%. Improved energy resolution of the imaging detector plays a key role in energy window data selection and reconstructed image quality enhancement.

Image Reconstruction

In coded aperture gamma imaging applications, data selection is based on energy windows. Uncorrected peak inconsistencies reduce detection efficiency and cause loss of true events, affecting image quality. In severe cases, this leads to incomplete projected images and ultimately imaging failure, particularly when incident rays are mainly absorbed by edge blocks. Therefore, correcting full-energy peak consistency across the detector' s effective area is necessary to improve imaging quality. Both simulation and physical experiments in this study used an I-131 source ($t_1/_2$ = 8.02 d) with 0.1 mCi activity. The I-131 point source, encoding board collimator, and imaging detector are aligned horizontally on the same axis. The distance between the I-131 point source and detector is 80 cm, while the distance between the encoding board collimator and detector is 5 cm.

Manufacturing variations prevent identical performance for each SiPM. The SiPM array response, signal acquisition, and readout are not perfectly synchronized, further aggravating full-energy peak inconsistency and reducing the amount of effective encoded image data. Corrected encoded images are more complete, enabling clearer image reconstruction. When the radioactive source is located at the center of the imaging detector' s useful field of view (UFOV), most valid information is collected in the central detector area. An incomplete encoded image does not cause reconstruction failure, and accurate radioactive source position reconstruction remains possible. However, full-energy peak inconsistencies can introduce artifacts in reconstructed images, reducing signal-tonoise ratio (SNR) and affecting reconstruction quality. When the radioactive source is located at the edge of the UFOV, most valid information concentrates in the peripheral detector area. Inconsistent full-energy peaks can cause severe loss of valid information, leading to deviations in reconstructed radioactive source position or complete imaging failure. Fig. 5d [Figure 5: see original paper] and Fig. 5e show uncorrected and corrected reconstructed images from the experiment, respectively. The uncorrected reconstructed image SNR is only 2.38. Corrected peak channels eliminate data outside the energy window, improving detector detection efficiency. Simultaneously, improved energy resolution enhances imaging detector performance, significantly increasing SNR from 2.38 to 5.37—a 125.6% improvement. Fig. 5 demonstrates that poor energy resolution of the uncorrected imaging detector causes data outside the energy window to be recognized as valid, resulting in low SNR and artifacts in reconstructed images. The corrected reconstructed image shows improved SNR, reduced or eliminated artifacts, and enhanced reconstruction quality.

4. Conclusions

Fig. 5 shows experimental encoded and reconstructed images. Fig. 5b and Fig. 5c represent uncorrected and corrected encoded images, respectively. The uncorrected encoded image in Fig. 5b exhibits data loss in the upper right and lower left corners, with more severe loss in the lower right corner. This results from true event loss in these blocks (as shown in Fig. 4b), leading to imprecise energy window data. Uncorrected encoded images in physical experiments suffer severe data loss, rendering image reconstruction infeasible. Beyond event position-induced peak inconsistencies, SiPM manufacturing variations also contribute to this effect.

This study demonstrates that not only pixelated crystal arrays exhibit inconsistent energy responses, but monolithic crystals show the same phenomenon. Different gamma-ray incident positions cause changes in energy deposition in monolithic crystal detectors, leading to energy response inconsistency. This reduces energy resolution and degrades radiation imaging system quality.

By performing step-scanning to obtain full-energy peaks at different incidence positions and leveraging the linear relationship between each block' s peak channel and the central block' s peak channel, we obtained the detector' s energy response functional correction matrix. A 32-FCNN localization algorithm positions incident rays to obtain positional information. Based on this positional information, corresponding correction coefficients from the energy response functional correction matrix are applied to correct the detector' s energy response. Correction results demonstrate that this method effectively improves energy response consistency, enhances energy resolution, and improves imaging quality.

In simulation experiments, this method improved full-energy peak consistency, reducing the FWHM of the 365 keV characteristic peak from 33 to 28 channels (15.2% energy resolution improvement) while enhancing detection efficiency. In physical experiments, the method improved full-energy peak consistency of the monolithic crystal imaging detector, producing evenly distributed peaks across the detector plane. For energy resolution, the method reduced FWHM from 53 to 38 channels at the 365 keV characteristic peak, achieving a 28.3% improvement. Regarding image reconstruction, the method reduced artifacts in reconstructed images, improved SNR from 2.38 to 5.37, and even transformed incomplete encoded images into fully encoded images for more accurate reconstruction.

The method proposed in this study minimizes or eliminates the impact of energy response inconsistencies, enhances detector energy resolution, enables more accurate energy window selection in imaging detectors, and improves image quality. These improvements are significant for enhancing nuclide identification accuracy and energy spectrum imaging quality.

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