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# 面向核医学单光子成像的钙钛矿半导体 γ 射线探测器

## 摘要

高能量分辨率、高空间分辨率和高灵敏度的 γ 射线探测器是提升核医学单光子成像性能的关键。传统 NaI(Tl) 闪烁体探测器在能量分辨率方面存在局限，而 CdZnTe 等半导体探测器虽具有较优性能，但其成本和材料制备仍限制了进一步推广。钙钛矿 CsPbBr3 半导体兼具高阻止能力、室温工作能力和潜在低成本优势，为发展新型核医学 γ 相机提供了新的材料基础。本工作围绕像素化 CsPbBr3 半导体探测器，构建了面向 99mTc 单光子 γ 成像的原型探测系统，并通过表面电荷收集优化、像素化电极设计、多通道读出和深度校正，实现了优异的能谱和成像性能。实验结果表明，该探测器在 99mTc 141 keV γ 射线下实现 2.5% 的整体能量分辨率，在 137Cs 662 keV 下实现 1.0% 的整体能量分辨率；点源和线源成像灵敏度达到 0.13%–0.21% cps/Bq，Derenzo phantom 假体成像空间分辨率约为 3.2–3.8 mm，证明了 CsPbBr3 钙钛矿探测器用于核医学单光子 γ 成像的可行性。
进一步地，针对像素化钙钛矿探测器中电荷输运、权重势分布、电荷共享和深度依赖脉冲形状等复杂物理过程，本工作建立了动态电荷感应与信号生成数值模拟框架。该框架集成 Geant4 能量沉积模拟、有限元电场与权重势计算、电子/空穴输运追踪、Shockley–Ramo 感应电荷计算以及 CSA 脉冲和 CR-RC4 成形信号模拟，能够从物理过程出发重建探测器的实时波形和能谱响应。模拟结果与实验脉冲和能谱具有良好一致性，并可用于分析电荷共享事件、作用深度效应和位置依赖的电荷收集损失。基于三维电荷损失校正，模拟能谱的能量分辨率由约 5.5% 改善至 1.5%，显示了该框架在探测器结构优化、信号校正和脉冲处理算法开发中的应用潜力。综上，本研究从器件性能验证和物理机理建模两个层面，展示了钙钛矿半导体 γ 射线探测器在下一代核医学单光子成像系统中的发展前景。

## 关键词

钙钛矿半导体；CsPbBr3；γ 射线探测器；核医学成像；单光子成像；电荷感应模拟

## Abstract

High energy resolution, spatial resolution, and detection sensitivity are essential for improving single-photon nuclear medicine imaging. Conventional NaI(Tl)-based scintillation cameras are widely used but limited by their moderate energy resolution, while CdZnTe semiconductor detectors provide improved performance but still face challenges related to cost and material growth. $CsPbBr_3$ perovskite semiconductors, featuring strong γ-ray stopping power, room-temperature operation, and potential cost-effectiveness, offer a promising route toward next-generation γ-ray cameras. In this work, we developed a pixelated $CsPbBr_3$ semiconductor detector system for 99mTc single-photon γ-ray imaging. Through surface charge-collection optimization, pixelated electrode design, multichannel readout, and depth correction, the detector achieved excellent spectroscopic and imaging performance. The overall energy resolution reached 2.5% at 99mTc 141 keV and 1.0% at 137Cs 662 keV. Single-photon imaging using point and line 99mTc sources demonstrated sensitivities of 0.13%–0.21% cps/Bq, and Derenzo phantom imaging resolved column sources with a spatial resolution of approximately 3.2–3.8 mm. These results demonstrate the feasibility of $CsPbBr_3$ perovskite detectors for nuclear medicine γ-ray imaging.
To further understand and optimize the detector response, we established a numerical framework for dynamic charge induction and signal generation in pixelated perovskite semiconductor detectors. The framework integrates Geant4-based energy deposition, finite-element electric-field and weighting-potential calculations, electron and hole transport tracking, Shockley–Ramo induced-charge modeling, and charge-sensitive amplifier and $CR\text{-}RC^4$ shaping simulations. It enables physics-based reconstruction of real-time waveforms and energy spectra, and provides insight into charge sharing, depth-dependent pulse formation, and position-dependent charge collection loss. The simulated waveforms and spectra show good agreement with experimental observations. Moreover, by applying three-dimensional charge-loss correction, the simulated energy resolution was improved from approximately 5.5% to 1.5%, indicating the potential of this framework for detector design optimization, signal correction, and pulse-processing algorithm development. Overall, these studies establish

a coherent pathway from experimental device demonstration to physics-based signal modeling, supporting the development of high-performance, low-cost perovskite semiconductor γ-ray cameras for future nuclear medicine applications.

## Keywords

perovskite semiconductor; $CsPbBr_3$; γ-ray detector; nuclear medicine imaging; single-photon imaging; charge-induction simulation

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