

# 基于多层阵列闪烁体的康普顿相机搭建

## 摘要

针对传统双层康普顿相机成像视场受限、散射光子利用率低以及半导体探测器敏感体积不足等问题, 本文提出了一种由前、后、左、右四个闪烁体阵列构成的成像结构, 探测灵敏体积为  $55\text{cm}^3$ , 实现对入射伽马射线  $360^\circ$  覆盖并有效提高了探测灵敏体积。最小成像单元采用独立 CsI(Tl) 晶体与单个硅光电倍增管 (SiPM) 直接耦合的方式, 提高了光收集效率并有效改善了能量分辨性能。在读出电子学设计中, 为降低系统通道数与整体成本, 采用一种串联读出方案, 将多个探测单元的输出信号合并为两路进行读出, 并结合自主研发的多通道数字化采集系统, 构建了一套结构紧凑、通道精简且稳定可靠的康普顿成像电子学系统。

测试结果表明, 该系统对  $^{137}\text{Cs}$  实现了 6.2% (FWHM) 的总能量分辨率和  $12^\circ$  的角度分辨率, 能够对来自不同方位的放射源进行有效识别与定位。同时, 本研究前瞻性地探索了人工智能技术在成像重建中的应用, 提出了一种基于多头注意力机制的机器学习直接成像方法, 实现了由原始探测数据到成像结果的端到端重建, 为提升复杂辐射场条件下的成像效率提供了新的思路。

研究表明, 所提出的多层阵列闪烁体的康普顿成像系统在实现  $360^\circ$  全方位成像视场的同时, 显著提高了探测灵敏体积。并且在成像灵敏度、响应速度和工程可实现性方面均表现出良好的综合性能, 在辐射环境监测、核安全与核应急、放射源快速定位以及核医学成像等领域具有良好的应用前景。

## 关键词

康普顿成像; 全向视野; 闪烁体探测器; 串行读出电路; 端到端重建

## Abstract

Traditional dual-layer Compton cameras face limitations such as a restricted field of view (FOV), low scattered photon utilization, and small sensitive volumes. To overcome these issues, we propose a novel imaging structure consisting of four orthogonally arranged scintillator arrays (front, back, left, and right). This configuration provides a total sensitive volume of  $55\text{ cm}^3$ , achieving a  $360^\circ$  omnidirectional coverage for incident gamma rays and effectively expanding the sensitive volume of the detection system. The fundamental imaging unit utilizes an individual CsI(Tl) crystal directly coupled to a single silicon photomultiplier (SiPM), an arrangement that enhances light collection efficiency and significantly improves the energy resolution. In the readout electronics design, to minimize the number of electronic channels and reduce the overall system cost, a multiplexed series readout scheme is implemented, merging the output signals from multiple detection units into two readout channels. Integrated with a custom-developed multi-channel digital data acquisition system, it forms a compact, streamlined, and highly reliable Compton imaging electronics system.

Experimental results demonstrate that the system achieves an overall energy resolution of 6.2% (FWHM) and an angular resolution of  $12^\circ$  for a  $^{137}\text{Cs}$  source, proving its capability to effectively identify and localize radioactive sources from various azimuthal directions. Furthermore, this study prospectively explores the application of artificial intelligence in image reconstruction. A machine learning-based direct imaging method utilizing a multi-head attention mechanism is proposed, achieving end-to-end reconstruction from raw detection data to the final imaging results. This approach offers a novel perspective for enhancing imaging efficiency in complex radiation fields.

In conclusion, the proposed multi-layer scintillator array Compton imaging system achieves a  $360^\circ$  omnidirectional field of view while significantly expanding the sensitive volume. The system exhibits excellent comprehensive performance in terms of imaging sensitivity, response speed, and engineering feasibility, demonstrating highly promising application potential in fields such as radiation environmental monitoring, nuclear safety and emergency response, rapid localization of radioactive sources, and nuclear medicine imaging.

## Keywords

Compton imaging; Omnidirectional sensitivity; Scintillator detector; Serial readout circuit; End-to-end reconstruction

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