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Development of a Compton imager based on bars of scintillator

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ABSTRACT

We have developed a compact Compton gamma-ray imager with a large field of view and a low channel-count that is capable of quickly localizing gamma-ray sources in the few hundred keV – several MeV range. The two detector planes (scatter and absorber) employ bars of NaI(Tl) read out by photomultiplier tubes (PMTs) located at each end. The long-range imaging performance has been tested from 392 keV to 1274 keV. An angular resolution measure of $2.72 \pm 0.06^{\circ}$ and an efficiency of $(1.79 \pm 0.04) \times 10^{-3}$ at 662 keV is obtained. A ^{137}Cs (662 keV) source equivalent to a 10 mCi source 40 m away can be located in 60 s with an uncertainty of about a degree. No significant degradation in imaging performance is observed for source angles up to 40° off axis.

1. Introduction

A portable Compton gamma-imaging device is a helpful tool in the prevention or clean-up of a radiological or nuclear incident. First responders require portable radiation detectors operating in the 0–3 MeV range that can be deployed in the field. To meet their needs, we have developed a Compton imager that is low-cost, ruggedize-able, and adaptable to suit a number of different surveying platforms (truck, helicopter, etc.). The detector is highly sensitive (capable of localizing a 10 mCi ^{137}Cs source at 40 m distance with degree-level precision in 60 s) making it suitable for real-life situations involving radiation sources that can be weak, distant or shielded.

Some highly compact Compton-imaging designs based on scintillator [1] and semiconductor technologies (CZT [2,3]) have been developed for commercial use. In the future, development in crystal growth technology may make these viable options for affordable larger-scale detectors. However, at present, these small ultra-portable detectors have limited sensitivity. In parallel, extremely large highly sensitive imagers have been developed [4–7]. However, these do not meet the requirements of agencies with limited funds, nor are they suitable for mounting onto multiple platforms. Our detector aims to operate in the middle range, by being both sensitive and portable (can be loaded into and out of a vehicle), while remaining affordable. A more expensive design based on scintillator with SiPMs has been developed [8]. The design presented in this paper employs long bars of scintillator (NaI(Tl)) with photomultiplier tube (PMT) readout, a combination well-proven for application in robust low-cost detectors operating in the field.

2. Compton imaging

In a Compton gamma imager, an incoming gamma ray of energy E_γ Compton interacts in a scatter detector, depositing energy E_1. The outgoing scattered gamma ray deposits its energy E_2 in an absorber detector. Neglecting Doppler broadening, the scattering angle between the initial and final-state gamma rays, θ_C, can be determined from the two energy deposits, via

$$\cos\,\theta_C = 1 + m_0c^2\left(\frac{1}{E_\gamma} - \frac{1}{E_2}\right) \tag{1}$$

where $E_\gamma = E_1 + E_2$ and m_0c^2 is the electron rest energy. As illustrated in Fig. 1, the position of the source lies somewhere on a cone of opening angle θ_C, where the cone axis is on the line between the two energy deposits. The location of the source can be reconstructed from the intersection of several cones.

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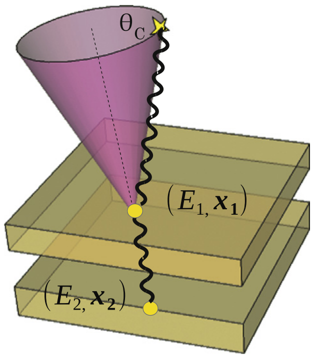

Fig. 1. Compton imager schematic depicting the energy and the position of the scattered electron, E_1, $\boldsymbol{x_1}$, recorded in the scatter plane, and the energy and the position of the scattered gamma ray, E_2 and $\boldsymbol{x_2}$, recorded in the absorber plane. The Compton cone, of opening angle θ_C, is calculated using the energy deposits and localizes the possible source locations.

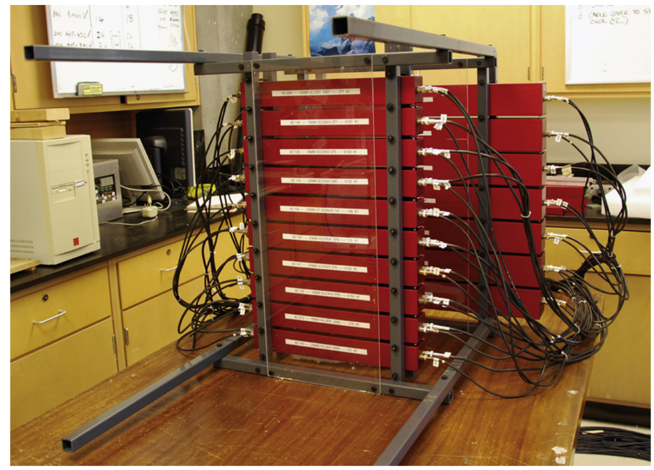

Fig. 2. Prototype consisting of ten scatter modules (front) and seven absorber modules (back) with a scatter-absorber spacing of 425 mm.

3. Bar design

We have designed, constructed and tested a Compton imager made of long bars of NaI(Tl) read out by PMTs fixed to the bar ends. Pulse-height sharing between the PMT signals is used to determine the position of the interaction. The use of long bars of NaI(Tl) offers an inexpensive design solution, as NaI(Tl) is relatively low cost, and the bar format requires few readout channels.

Long scintillation bars have previously been employed in Compton imagers where the energy deposits are large [5], however to employ this technique at lower energies, an optimization of the attenuation length of the bars is needed. Studies have been done to look at the effect of tuning the attenuation length of scintillator in order to optimize its position reconstruction [9–12], which holds well at high incident gamma-ray energies where one is not photo-statistics limited. However, operating at low energies (less than 150 keV in the scatter layer for incoming 662 keV gamma rays) requires tuning the bar attenuation length to optimize the overall performance of the imager. To this end, a highly detailed Monte-Carlo simulation using optical transport was developed to determine the optimal attenuation length of the scintillator bars. A prescription was then developed to manufacture these bars for the detector.

4. The detector

Previous work has shown that for the scatter plane, the optimal thickness for one Compton scatter of 662 keV gamma rays in NaI (Tl) is ~20 mm [13]. With this thickness, approximately 20% of 662 keV gamma rays Compton scatter once and exit. For the absorber plane, a thickness of 40 mm is chosen, a compromise among increasing the absorption fraction, maintaining comparable lateral and longitudinal position resolution, and matching the bar cross-section with commercially available PMTs.

A photograph of the full-scale prototype is shown in Fig. 2. The modular scatter and absorber layers are 425 mm apart (center to center) and mounted on a frame constructed of 1/2 in. PVC tubing. The scatter plane consists of ten $16 \times 16 \times 200\ \text{mm}^3$ and $20 \times 20 \times 200\ \text{mm}^3$ bars of NaI(Tl) and the absorber plane consists of seven $40 \times 40 \times 400\ \text{mm}^3$ bars of NaI(Tl).

An overview of the scintillator dimensions and the PMT sizes, QEs and model numbers of all the components is provided in Table 1. In the scatterer, we used both Super bialkali (SBA) PMTs, with QE ~35%, and Ultra bialkali (UBA) PMTs, with QE ~43%. In the absorber, we used standard PMTs. The scintillator was purchased from Scionix, Saint Gobain and Hilger Crystals[2] while the PMTs were from Hamamatsu.[3]

Table 1
Summary of the detector components making up the scatter and the absorber plane. Only four of the seven absorber bars were included in the detector for assessing the performance for reasons discussed in Section 6.

Plane	Scintillator		PMT		
	Number	Size (mm^3)	Model	Size (mm)	QE
	5	$20 \times 20 \times 200$	R8900U-100	23.5	SBA (35%)
Scatter	4	$16 \times 16 \times 200$	R8900U-100	23.5	SBA (35%)
	1	$16 \times 16 \times 200$	R7600U-200	18.0	UBA (43%)
Absorber	7	$40 \times 40 \times 400$	R6236	54.0	23%

Each NaI(Tl) bar is encapsulated in aluminum with a quartz window located at each end. The bars are read out by PMTs glued to the windows. The entire setup is positioned inside a 1/16 in. thick aluminum container (see Fig. 3) and packed with foam to protect the assemblies from mechanical shock. The PMT high voltage (HV) is supplied by a CAEN[4] SY 2527 Universal Multichannel Power Supply System.

The data acquisition uses a combination of VME, CAMAC and NIM standards. The PMT pulses are amplified by a factor of ten (Phillips Scientific[5] 776) and split into two sets. The first set goes into a discriminator (Phillips Scientific 705) and participates in a hardware coincidence effectively requiring one or more end-to-end coincidences in the scatter layer together with the same pattern in the absorber layer (Phillips Scientific 754 Logic Units). The second set of amplified PMT signals is fed directly into a 48-channel 10-bit VME VF48 digitizer [14] and integrated on-board when a coincidence is present. The resulting charge values are then transferred to a computer via a USB-VME bridge (CAEN V1718). Immediately, a software cut is made to include only events with exactly one scatter bar hit and one absorber hit, where a hit denotes that both the left and right PMTs of a given bar are above threshold. The energy deposit is reconstructed in a given bar by summing the signals of the left PMT (S_1) and right PMT S_2. The position is reconstructed using the ratio of these two signals, S_1/S_2.

[2] Scionix: www.scionix.nl Saint Gobain: www.saint-gobain.com Hilger Crystals: www.hilger-crystals.co.uk
[3] www.hamamatsu.com
[4] www.caen.it
[5] http://www.phillipsscientific.com