35th Annual International Conference of the IEEE EMBS
Osaka, Japan, 3 - 7 July, 2013

EGS5 Simulations to Design a Ce:GAGG Scintillator Based Compton Camera

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Abstract—**$Ce^{+3}: Gd_3Al_2Ga_3O_{12}$ (Ce:GAGG) is expected to be promising scintillator for PET, SPECT, and gamma camera applications because of its attractive properties. We designed a Compton camera based on Ce:GAGG, both as scatterer and absorber, for imaging and radioactivity measurement of point sources. The two important parameters sensitivity and spatial resolution are determined for 4×4 pixels, each pixel of size $1 \times 1cm^2$, for both scatterer and absorber. Our main focus in this paper is to image a distant source for which sensitivity is of prime importance. High sensitivity and light weight are two important advantages of Compton camera for distant source imaging and the availability of Ce:GAGG $3 \times 3mm^2$ pixel size is expected to give a spatial resolution of $\sim 5mm$ for medical applications as well.**

I. INTRODUCTION

As scintillating materials combined with photo detectors are widely used for the detection of high energy gamma rays, thus, great efforts were made for the development of more efficient, fast decaying and easily grown scintillators [1]. $Ce^{+3} : Gd_3Al_2Ga_3O_{12}$(Ce:GAGG) is expected to be promising scintillator for PET, SPECT, and gamma camera applications because of its attractive properties like very high light yield ($\sim 46000 photons/Mev$), longer light wavelength ($500nm$), decay time ($\sim$ $90ns$), good energy resolution (4.9% @$662kev$ for $5 \times 5 \times 1mm^3$ sample and 14.4% @662kev for $0.5 \times 0.5 \times 5mm^3$ sample), high density ($6.6g/cm^3$), and non-self radiation (as no Lu component)[1]-[3]. The combination of longer wavelength of the scintillation light, emitted from GAGG, with Silicon photomultiplier (Si-PM) produces large signals due to higher quantum efficiency of Si-PM for longer wavelengths. Thus, block detectors of higher spatial resolution may be obtained and as a result ultrahigh resolution, less than $1mm$, coincident imaging system are developed by S. Yamamoto et al. [2]. The Ce:GAGG should be a promising material for the study of neutrinoless double beta decay of ^{160}Gd by employing the pulse shape discrimination capability against $\alpha-$ ray induced background because of its advantage in particle detectors, where the discrimination between $\alpha-$rays and $\frac{\beta}{\alpha}$ should be required [3]. Compton camera is considered to be a very promising imaging device widely used in nuclear medicine, molecular imaging, astrophysics, industrial survey, homeland security and medical purposes [4]-[5]. Based on electric collimation principle and using a geometric interpretation of Compton scattering, a quantum mechanical phenomenon, to decide the direction of incident gamma, the Compton camera overcomes the disadvantages of conventional medical imaging devices like PET and SPECT which use mechanical collimators. The main advantages of Compton camera include high sensitivity, high resolution, wide field of view, compactness, low patient dose, multiple radioisotope tracing capability, and inherent 3D imaging capability [6]-[7]. By considering the advantages of Compton camera and properties of Ce:GAGG scintillator, we present a Compton camera which uses Ce:GAGG material both as scatterer and absorber. Our main focus is to develop a Compton camera which is capable of imaging a distant source within reasonable time interval for environmental radiation monitoring. Higher sensitivity at large distance and light weight are the basic motives to select Compton camera for our application.

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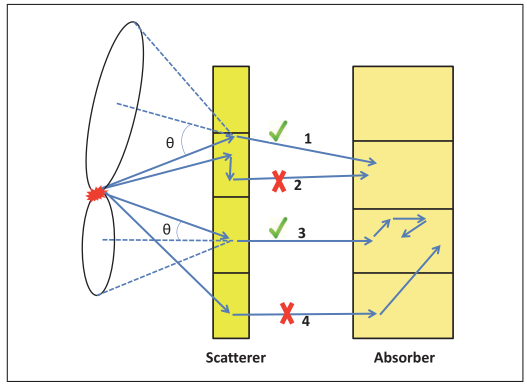

Fig. 1. Schematic of Compton camera with four different possible events. 1 and 3 are desired and 2 and 4 are undesired events. The common point of cones gives the position of point source.

II. CE:GAGG BASED COMPTON CAMERA

A Compton camera uses two position sensitive detectors as scatterer and absorber. The scatterer determines the location of Compton scattering and the deposited energy in the scatterer (or electron recoil energy), E_1, while the absorber determines the location and energy of the photon, E_2, absorbed in it. Knowing the energy deposited in scatterer, E_1, incident energy, $E = E_1 + E_2$, and employing coincident detection mode, the scattering angle θ can be determined by using Compton interaction relationship which is given by,

$$\cos(\theta) = 1 - m_e c^2 . (\frac{1}{E_1} - \frac{1}{E}). \quad (1)$$

In (1), $m_e c^2$ is electron rest energy. If the coordinates of first and second interaction points are known, together with θ, the gamma emitting source lies on the surface of cone with θ as semi-angle and axis passing through two interaction points as shown in Fig. 1. An emitted photon scattered from first detector, scatterer, and absorbed in second detector, absorber, is called true event and results in one cone. A series of true events would generate a series of such cones. These cones have one common point which defines the position of imaging point. Thus, scatterer and absorber have different requirements and their choice is an important consideration. Monte carlo radiation transport Electron Gamma Shower 5 (EGS5) code was used for simulations of Compton camera and 10^7 gamma rays of energy $662keV$, emitted by a Cs^{137} point source, and were made incident on scatterer faces for the material properties study and on the face of scatterer for Compton camera study. As Cs^{137} is more commonly produced in uranium-235 nuclear reactors (and hence very problematic especially after nuclear accidents and needs to be detected for public safety) and easily available in laboratories for characterization experiments, hence we selected this isotope for EGS5 simulations to design the proposed Compton camera. The history was terminated either the particle left the area of interest or its energy is less than a certain cut off value. We selected absolute intrinsic efficiency because of its independence to source position and describes the material properties. We characterize Ce:GAGG to be used as scatterer and absorber as follows,

A. Scatterer

The scatterer in Compton camera makes electronic collimation by scattering gamma ray incident on it which on absorption in absorber makes a true event for image reconstruction. As the scatterer determines the location of interaction and energy deposited, hence, it is highly required that scatterer must have superior scattering properties and reasonable energy resolution. On the other hand, a gamma ray scattered multiple times in the scatterer only deteriorates the image and is highly undesired. The single Compton scattering events and good event ratio, which is ratio of single Compton scattering events to total scattering events (i.e. single and multiple Compton scattering events), are figure of merit for scatterer. The situation is described in Fig. 1 and the events are classified as desired and undesired events. For desired events, single Compton scattering is desired along with good event ratio. Fig. 2 shows the detection properties of Ce:GAGG segmented detector block of $1 \times 1cm^2$ pixels size. With increase in detector thickness, the photoelectric events, which also include the full-energy events as result of multiple Compton scattering in same pixel and finally absorbed, are increased and the difference between Compton scattering events and number of total detected events increases. Thus, small thickness is preferred for scatterer, as also clear from Fig. 3 that multiple Comton scattering events increase with thickness. Good event ratio with detector thickness is shown in Fig. 4 which suggests that scatterer should have smallest possible thickness e.g. $1mm$ in present case but at this thickness the total efficiency is very small so in order to have reasonable sensitivity, we have to sacrifice this ratio.

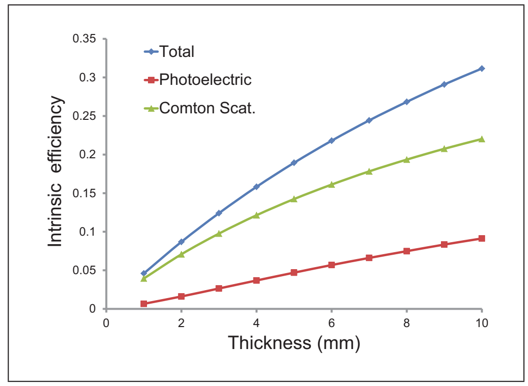

Fig. 2. Intrinsic efficiency (total, photoelectric absorption, and Compton scattering) versus detector thickness for $662keV$ gamma rays energy.

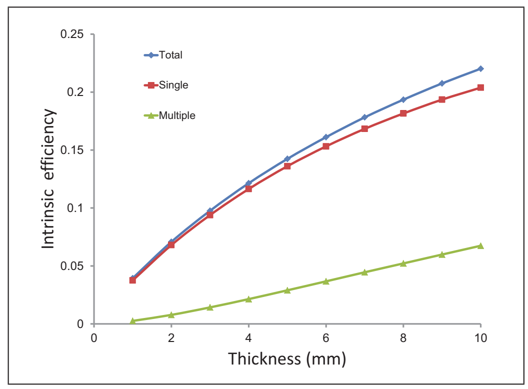

Fig. 3. Intrinsic efficiency (total, single, and multiple Compton scattering) versus detector thickness for $662keV$ gamma rays energy.

B. Absorber

For absorber, the higher photoelectric absorption is preferred. As clear from Fig. 2 that photoelectric or full-energy absorption increases with detector thickness so maximum possible thickness is preferred. Thus, the selection of absorber is easy but on the other hand, the large thickness may increase the parallax error and degrade the image quality by increasing the spatial resolution which we will consider and discuss in later work. As the events incident on absorber are coming from scatterer and may have different energy values so Fig. 5 shows the intrinsic efficiency of Ce:GAGG for different energy values for detector thickness of $10mm$. It is clear that full-energy efficiency decreases with increase in incident energy.

III. Basic performance of gamma camera

The two most important parameters which specify the detection and imaging capabilities of a Compton camera are the sensitivity and the spatial resolution. Sensitivity is more important while imaging distant sources in shortest possible time interval whereas, spatial resolution is more important in medical applications. The above mentioned parameters

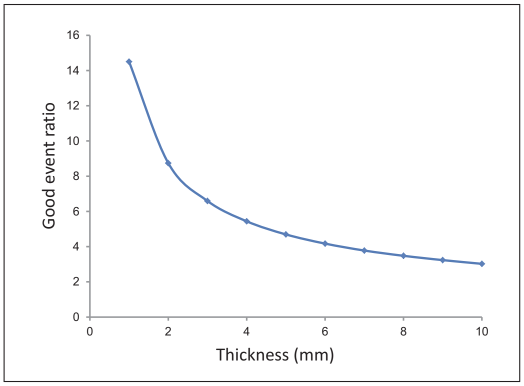

Fig. 4. Good event ratio versus detector thickness.

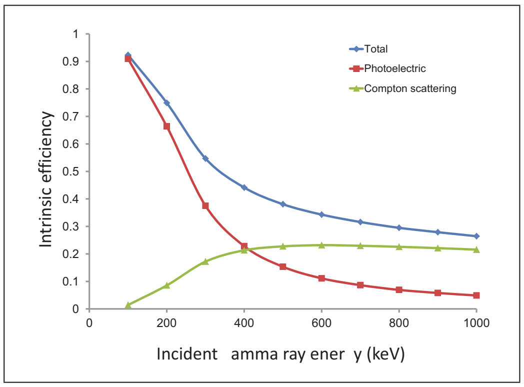

Fig. 5. Intrinsic efficiency versus incident energy for $10mm$ detector thickness and $662keV$ gamma rays energy.

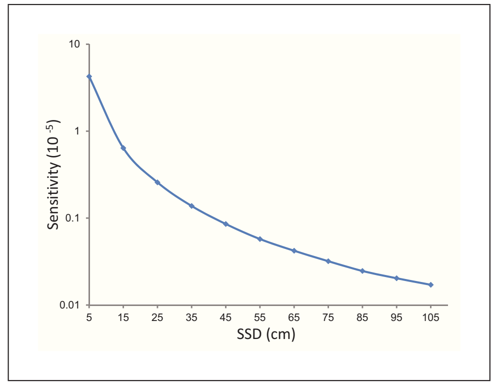

Fig. 6. Sensitivity versus SSD for $662keV$ gamma rays energy on semi-log scale.

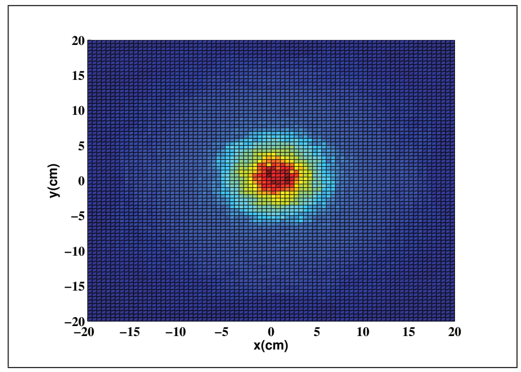

Fig. 7. Image of point source at $5cm$ SAD.

depend on source-scatterer distance (SSD) and scatterer-absorber distance (SAD) for particular scatterer and absorber pixel sizes. In order to obtain the image of point source, we selected $1 \times 1cm^2$ pixel size for both scatterer and absorber. The scatterer thickness was selected $2mm$ and absorber thickness as $10mm$. Using EGS5 simulation code and by generating 10^7 gamma rays which are in such a direction that incident on scatterer face and the information of scatterer and absorber pixel numbers alongwith the deposited energies is stored. If the deposited energy in scatterer was greater than or equal to $0.1keV$ and that in absorber was greater or equal to $300keV$, the event was registered as true count. However the criteria for counts used in image construction was that sum of energies deposited in scatterer and absorber should be greater than or equal to $400keV$. The SAD was assumed to be $5cm$, for SSD study, and point source is moved from $5 - 105cm$ in step of $10cm$ and sensitivity is determined at each distance for true coincident events. The variation in sensitivity with SSD is shown in Fig. 6. From sensitivity, we can find the measurement time required to obtain reasonable counts for image reconstruction.

In current application, our main focus is to image a distant source and in that particular case, sensitivity is more important to obtain reasonable counts in shortest possible measurement time interval. Thus, simple backprojection technique is used to form the image with difference of giving weight to image pixel which contains more circumferential length of ellipse in it. Using the stored information, which gave the coordinates of interaction points and deposited energy in scatterer and absorber, θ was calculated and was used to generate a cone for corresponding true event. Finally we assumed an imaging plane at given source distance and obtained an ellipse as result of interaction of cone with imaging plane. The pixels of imaging plane, where ellipses from all cones were overlapping, were stored [8]. The intensity of each pixel, in terms of weighted counts, is converted to color value and the so obtained image of a point source at $5cm$ SSD is shown in Fig. 7. We considered the pixel with maximum counts as center point and determined the full width half maxima (FWHM) of the distribution in either direction. Variation in spatial resolution, in terms of FWHM, with SSD is studied. The spatial resolution values of $8cm$, $35cm$ and $50cm$ were determined from images for SSD of $5cm$, $55cm$, and $105cm$ which shows that this Compton camera is not suitable for medical application. However it may be used to image the distant sources, and hence determine present activity, for which spatial resolution is not very important. The recent reported results about pixel size of $3 \times 3mm^2$ regarding coincident imaging system show much promise and we are hopeful that using pixel size of $3 \times 3mm^2$ may be very helpful for obtaining the spatial resolution $\sim 5mm$ is possible.

IV. Conclusion

A Compton camera based on promising scintillator Ce:GAGG, both as scatterer and absorber, is presented. The poor spatial resolution, $8cm$ at $5cm$ SSD, shows that this camera is not suitable for medical applications. However, it may be used for imaging distant point sources with high sensitivity at the cost of spatial resolution. We expect that using pixel size $3 \times 3mm^2$, we can obtain the spatial resolution suitable for medical applications.

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