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A COMPTON CAMERA FOR SPECTROSCOPIC IMAGING
FROM 100 keV to 1 MeV

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A Compton Camera for Spectroscopic Imaging from 100keV to 1MeV

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Preliminary Exam

Based on the requirements for a PhD degree at
North Carolina State University
in the department of
Nuclear Engineering

Advisory Committee

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Abstract

A review of spectroscopic imaging issues, applications, and technology is presented. Compton cameras based on solid state semiconductor detectors stands out as the best system for the nondestructive assay of special nuclear materials. A camera for this application has been designed based on an efficient specific purpose Monte Carlo code developed for this project. Preliminary experiments have been performed which demonstrate the validity of the Compton camera concept and the accuracy of the code. Based on these results, a portable prototype system is in development. Proposed future work is addressed.

Introduction

The goal of spectroscopic imaging is to provide information related to the spatial distribution and identity of radioactive nuclides. This can be accomplished by remote detection of the radiation produced by decay of nuclear materials. Imaging systems exist for both gamma ray and neutron imaging, however our focus will be given to the gamma systems. Specific applications of spectroscopic imaging systems include improvements in accuracy for the nondestructive assay of nuclear materials, medical imaging, and gamma ray imaging for astrophysics. The first two techniques cover energy ranges from about 100keV to 1MeV, while the upper limit for telescopes approaches 30MeV to image high energy cosmic radiation sources.

Important issues in spectroscopic imaging are energy resolution of the detectors in a system, spatial resolution, field of view, and time required for image acquisition. The ability of a system to distinguish different isotopes is directly related to its energy resolution. Spatial resolution defines the ability of a system to resolve two distinct, spatially separated radioactive sources. Field of view defines the solid angle accepted by the system. The amount of time required to examine a given area depends on the system's field of view and detection efficiency. Table 1 contains the first three parameters for a collection of typical gamma ray imaging systems. Technical issues that must be addressed in designing a Compton camera are count rate limitations, random coincidences, multiple Compton scattering, spatial resolution dependencies on detector sizes and energy resolution, and low energy detector cutoff (associated the detector noise). Complications for spectroscopic imaging may include attenuating materials between the origination of the gamma ray in the nucleus and the detector. Finite source sizes produce source self attenuation. Intervening materials between the source and detector may also distort the photon energy spectrum. These complications are defined by the scene to be imaged and are usually out of our control.

The motivations for this work are given in the next section followed by a review of gamma ray imaging systems highlighting limitations of existing designs and the promise of Compton cameras providing a superior match with our requirements. Results of

numerical simulations to predict Compton camera performance are reviewed, including two methods of image reconstruction. Experimental measurements were made with CdZnTe detectors and the implications towards system design are presented.

Objective

The main imaging system requirements for the nondestructive assay (NDA) of special nuclear materials (SNM) are good energy resolution ($<5\%$ at 662keV) to discriminate between different radioisotopes, wide area imaging, and system portability [1]. SNM is material that could be fabricated into a fission weapon, particularly highly enriched uranium (HEU) and low burnup plutonium. Each of these materials has complex energy spectra, as shown in figure 1.

Figure 1 Pulse height spectra of highly enriched uranium and low burnup plutonium measured with a CdZnTe detector.

The principal gamma ray signature for highly enriched uranium is 186keV line from the U235 isotope and for low burnup plutonium is the 414keV line from Pu239. The goal of NDA in this context is to quantify location and mass of SNM in processing equipment, research facilities, and in facility decontamination and decommissioning. By identifying the location and extent of a SNM deposit, a more accurate mass survey can be conducted by relaxing related assumptions. Our objective is to provide the basis to build a well engineered system capable of imaging these particular isotopes and the others associated with this material, which emit gamma rays in the range of 100keV to 1MeV.

Gamma Ray Imaging Systems

Of the multitude of gamma ray imaging devices that exist, they can be separated into two basic designs: mechanically and electronically collimated systems. Mechanical collimation is provided by single aperture or an array of holes in a radio-opaque shield in front of the detector. Electronic collimation is provided by time coincidence circuitry between spatially separated detectors. High pressure xenon detectors, previously used in high energy physics experiments, form a new class of imaging system for this energy regime that does not fit into either of the above categories.

A spectroscopic imaging system in its simplest form is the scintillation detector. A NaI(Tl) crystal attached to a photomultiplier, is sensitive to the energy of a detected gamma ray. When coupled to a multichannel analyzer, this class of detectors provides the energy spectrum of detected photon flux. By providing a single aperture mechanical collimator made of tungsten or lead, the scintillation detector is now sensitive to the direction of incoming gamma rays. This type of system provides information about one point in a two dimensional spatial image. This point represents the scene integrated over the field of view defined by the collimator. Therefore, the collimator aperture must be scanned over an area to create an image.

If the simple photomultiplier is replaced with a position sensitive photomultiplier, the scene is no longer integrated over the field of view. In order to provide spatial resolution in the image, collimator aperture is greatly reduced to about 5mm in diameter. This is the principle behind a pinhole camera. Of course, detection efficiency also decreases with smaller apertures. A limitation commercially available systems is that a discriminator window must be set around an isotope's photopeak energy to image that particular isotope. If more than one isotope is contained in the scene, a separate image acquisition must be made for each isotope with the appropriate discriminator settings.

In coded aperture systems the pinhole aperture is replaced with a multiple aperture mask which provides multiple redundant shadows of the scene on the detector crystal [2, 3]. If the effect of the mask is deconvoluted from the recorded image via Fourier transforms, the scene is recovered. This technique was originally developed to enhance the signal to noise ratio obtained from a pinhole camera. These systems are especially successful in recovering the most intense source in a multisource scene. A disadvantage is the optimal mask pattern is scene dependent. Extended source distributions present problems for this technique, since the shadow pattern cast by the mask may not be unique.

The Anger camera is a large NaI(Tl) crystal coupled to an array of photomultipliers [4]. Mechanical collimation is used to divide the scene into discrete spatial elements on the crystal. The array of photomultiplier tubes provides a position sensitive readout of the crystal. It is the standard imaging device in nuclear medicine. These systems typically have large field of view. The size and shape of the collimator holes, in large part, determines the system's spatial resolution and detection efficiency. Three dimensional images of the isotope distribution can be afforded by rotation and translation of the camera around the patient. This provides projection views, which can then be combined

by standard tomographic techniques. This technique has been coined by the term Single Emission Computed Tomography or SPECT. In general, for mechanically collimated systems, the spatial resolution begins to suffer due to gamma rays over about 250keV penetrating "opaque" portions of the collimator. These systems are large and since they are based on NaI detector technology, they have poor energy resolution.

The time projection chambers have been proposed and built for spectroscopic imaging in the energy range of 30keV to 1MeV [5]. It is like a Wilson cloud chamber, in that it provides quantitative measurements of particle tracks. A high pressure Xenon gas (9-20atm) is contained within a chamber instrumented with a position sensitive grid of photomultiplier tubes. An initial interaction in the gas results in a prompt scintillation, which gives a trigger signal of the beginning of an event. If incoherent scatter of the gamma ray occurs, the scattered electron produces ionization clusters in the gas. A uniform electric field accelerates the secondary electron clusters produced by the interactions towards a light generating gap over the position sensitive grid. This light generating gap is region of high electric field where the drifting electrons produce electroluminescence of the gas. The time it takes the light photons to reach the measurement grid from the beginning of the prompt scintillation gives the depth of the scattered electron track within the chamber. The projection of the photons on the position sensitive grid gives the remaining information needed to reconstruct the three dimensional track of the scattered electrons. Summing the response of all the photomultipliers, a signal is recorded which is proportional to the energy deposited in each cluster. By measuring the energy and direction of both the scattered gamma and Compton electron, the direction and energy of the incoming gamma ray can be deduced. Note that all the relevant measurements are made within a single detector system. These devices have low noise characteristics making them ideal for low energy measurements below 100keV. Detection efficiency is good due the high pressure Xenon gas, but they are count rate limited and errors in reconstruction are introduced by small angle scattering of the electron before its track is determined.

Compton camera systems provide localization of the source distribution by time coincident measurements of the products of a Compton scattering interaction in two spatially separated detectors. A reconstruction of the original photon direction is made from the location of the two detectors and the energies deposited (corresponding to the Compton scattered electron in the first detector and the photoelectric absorption of the scattered gamma ray in the second detector). This information from one Compton scattering event provides a conical surface representing the possible directions of the original gamma ray, see figure 2. If the detectors relative positions are changed and many events are recorded, intersection of the reconstructed cones provides source localization. The detection efficiency of the two detector system is improved by including arrays of detectors all recording measurements simultaneously. Since the collimation is provided electronically, the field of view includes the entire hemisphere in front of the detector. Data acquisition is performed without using a discriminator. The same data set contains information about all the radioactive nuclides in the scene. Image reconstruction can then be used to provide image templates identifying specific locations of each radioisotope. In order to provide competitive detection efficiency with Anger

camera systems, arrays of detectors each recording data simultaneously must be used. Improvements in detector technology has resulted in the commercial availability of solid state detectors that operate at room temperature with good energy resolution. Enhanced system portability is attained by relaxing the detector cooling requirement.

Table 1

	Energy Resolution (%) (Cs-137)	Spatial Resolution (Radians)	Field of View (Steradians)
Scintillation Detector*	7.5	>0.2	0.2
Pinhole Camera [6]	12-25	0.07-0.14	0.4-0.9
Anger Camera [7]	13.5 (Co-57)	0.005-0.012	1.5-2.2
Coded Aperture	12-25		
Time Projection Chamber [5]	2.7 (Co-57)	0.26	~6.2
Compton Camera†	2.5-4	0.11-0.26	~6.2

*NaI(Tl) crystal 2.54cm in diameter and 1.27cm thick, with a collimator 2.54cm in diameter and 2.54cm deep.

†Compton camera specifications are for prototype design based on CdZnTe detectors, presented in text.

Compton Camera Systems

A review of existing Compton camera hardware starts with a system developed for telescope applications beginning in 1971 at the Max Plank Institute[8, 9]. It matured into the COMPTEL package implemented on the Compton Gamma Ray Observatory satellite. The COMPTEL system is comprised of 7 liquid (NE213A) scintillation detectors as the first plane detector array and 14 NaI(Tl) detectors as the second plane detector array. Each of the liquid scintillator cells is 28cm in diameter and 8.5cm deep instrumented with eight photomultiplier tubes. The individual NaI(Tl) detector crystals are 28.2cm in diameter and are 7.5cm thick instrumented with seven photomultipliers. The system is designed to image weak, distant sources in 1-30MeV range. It has an energy resolution of 9% at 1MeV, spatial resolution of 0.02, and a field of view of 1 steradian.

Efforts to apply this technique to nuclear medicine at the University of Southern California in the 1980's resulted in a design which used 16 high purity germanium detectors in the first plane array and single uncollimated Anger camera (Pho/Gamma IV) as the second plane detector [10-13]. The individual Ge detectors dimensions are 5mm square and 6mm thick. They are contained in a specially designed cryostat. The Anger camera is 20cm in diameter and 1.27cm thick. This device was designed to image spatial

distributions of a pharmaceutical labeled with Tc99m injected into a patient. This isotope emits a 140keV gamma ray. Note that no other sources (other than K40, with a 1.5MeV gamma ray, in small, naturally occurring quantities) are present in the camera's field of view for this technique.

This same device was improved in 1993 at the University of Michigan by replacing the Anger camera with 16 NaI(Tl) detectors, 19.1mm in diameter by 50.8mm in length [14, 15]. These detectors were arranged in an azimuthal ring behind the Ge array. The system's spatial resolution was measured at 0.1 radians. Their target application was to measure industrial gamma ray fields with spatially extended sources composed of more than one isotope. They are the first group to demonstrate mutli-isotope imaging capability of a scene containing Cu64 (0.511MeV) and Zn65 (1.116MeV) spatially extended sources. A common thread in all these systems is the use of detectors (NaI(Tl)) with poor energy resolution.

The Naval Research Laboratory has designed and tested a system based entirely on high purity Ge detectors for the purpose of characterizing unknowns in radioactive waste containers [16]. These detectors have energy resolutions of 0.3% at 1333keV, which is best possible of existing detector technology. The associated cryostats used for cooling the detectors makes the system too large to fit with our portable system requirement.

Code Development

Our approach to designing a system begins with the development of code, which can be used to optimize a Compton camera for our needs. Analog Monte Carlo code approaches are inadequate for system optimization due to the long computation times required for each design iteration. The MCNP code used with variance reduction techniques would work, although obtaining tallies corresponding to time coincident measurements is a difficult and dirty process. In response to these limitations, a specific purpose Monte Carlo code, FARRAH (Forcing All Required Reactions, All Histories), was written to simulate the Compton camera response to radiation sources. The principle of forcing is used to make each history result in a partial success [17]. This technique is based on sampling only the range of a stochastic event that can lead to a success. The weight of the history is adjusted at each such event to reflect restricted sampling range. Let a particular stochastic event be governed by a normalized probability distribution function $f(x)$, where x has the range from $x_{\min}$ to $x_{\max}$. The modified pdf $\hat{f}(x)$, for forcing x between x_1 and x_2 is obtained from

$$\hat{f}(x) = \frac{f(x)}{\int_{x_1}^{x_2} f(x)dx} \text{ for } x_{\min} \leq x_1 \leq x \text{ and } x \leq x_2 \leq x_{\max}.$$

The associated weight for forcing x between x_1 and x_2 is

$$w = \int_{x_1}^{x_2} f(x)dx.$$

By eliminating ranges of zero probability, no computation time is spent on histories that do not contribute to the result. The FARRAH code includes effects from detector response functions and multiple Compton scattering. For details of the content and methodology of the code, see Appendix A.

Another Monte Carlo code was written in an almost completely analog framework to check the validity of these techniques. The only forcing used in the code was to force emission from the source in the direction of the first plane array of detectors. The run times of the analog code is on the order of days to get statistics below 20% while FARRAH obtains statistics below 5% in minutes for the same initial problem geometry. It should be noted that neither code takes into account surrounding materials such as support structure, floor, walls, etc. A comparison of the results from each code is contained in the Results section.

Image Reconstruction

Image reconstruction in 2-D image space for Compton camera data (simulation or experiment) is done by one of two techniques. The most direct technique is event circle reconstruction [22]. The image space is created by projecting a cone reconstructed from the locations and energies deposited in the detectors on a sphere for each recorded event. This couples the spatial resolution of the system to the energy resolution of the detectors. The Compton energy angle relationship is used to determine the cone half angle θ_s , from the energy deposited in each detector

$$\cos(\theta_s) = 1 + m_0 c^2 \left(\frac{1}{E_{dep1} + E_{dep2}} - \frac{1}{E_{dep2}} \right).$$

The axis of the cone is on the direction connecting the centers of the two detector elements. The apex of the cone is located at the center of the first detector element. Since the gamma ray could have originated from any of the directions on the surface of the cone directed towards the apex, the azimuthal angle is randomly sampled over the full range of 2π . A generic diagram of this is contained in Figure 2.

Figure 2 Generic Compton camera event diagram.

The result for each event is added to next. After many events are processed, the location of the source is reinforced such that it stands out over the background. The image space is represented by a rectilinear mapping of the spherical coordinates θ and ϕ , so the expected elliptical patterns for a single event appear sinusoidal in this image space. Problems with this technique involve high background and asymmetric point spread functions.

Image reconstruction is also performed by the Expectation Maximum-Maximum Likelihood (EMML) technique [23]. The EMML method provides image reconstruction by casting the problem in terms of a joint probability function and iterating until the solution converges. Each recorded event is binned into an ordered, discrete event vector parameterized by the spherical coordinates of the cone axis and half angle. Next, a probability function is constructed for each discrete element in the event vector. An initial, nonzero estimate of the image is provided. The estimate of the image is updated each iteration by the number of events in each event vector bin and its associated probability function. This technique improves detail and reduces background. A comparison of these two methods is contained in the Results section.

Compton Camera Experiment

A preliminary experiment was setup to test the detectors, electronics, and limiting technical issues. Two CdZnTe coplanar grid detectors were setup with time coincidence electronics and a digital data acquisition system to record the data. A block diagram of the setup and electronics settings, along with a photograph of the system, is presented in Appendix B. The timing electronics were calibrated using a Na22 source, which decays with a positron emission component. This is convenient due to the two correlated 0.511MeV gamma rays produced by the annihilation of the positron. In addition, a 1.275MeV gamma ray is present from Na22 decay, which provided us with a two point energy calibration.

After the detectors were calibrated, they were setup in a geometry, depicted in Figure 3, in relation to a 1.177mCi Se75 source.

Figure 3 Experiment geometry. The red circle represents the source, the first plane detector locations are in green, and the second plane detector is blue.

The first detector was 10x10x5mm in size and has an energy resolution of 4% at 0.662MeV. The second detector was 10x10x10mm in size and has an energy resolution of 2.5% at 0.662MeV. The second detector is shielded from the source by 5cm of bismuth to reduce background contribution from random coincidences. An actual photograph, shown in Figure 4, illustrates that the first detector is positioned on a platform, which can be raised to change the relative position between the source (in the lead cave) and second detector.

Figure 4 Photograph of experimental detector arrangement

Three measurements were made to provide preliminary data for a Compton camera prototype, where the first detector was raised in 2cm increments. Ten thousand coincident events were recorded at each position.

Results

In order to check the validity of the forcing techniques contained in FARRAH, an analog Monte Carlo simulation was performed with the same geometry. Figure 5 illustrates the simulation geometry, 81 8x8x4mm CdZnTe detectors in the first plane, one 10x10x10mm CdZnTe detector in the second plane, and a monoenergetic 0.662MeV point source.

Figure 5 Simulation geometry.

Figure 6 shows a comparison of the spatial efficiency calculated in each code for detected events in the first plane array. The calculated standard deviations are presented in Figure 7. Figure 8 show the images produced by event circle reconstruction for each code. The FARRAH code produced these results in minutes while the analog code's run time was on the order of days.

Figure 6 Spatial efficiency calculated by FARRAH code (left) and analog code (right).

Figure 7 Standard deviation of spatial efficiency calculated by FARRAH code (left) and analog code (right).

Figure 8 Simulated images created by event circle method for FARRAH code (left) and analog code (right).

A comparison of image reconstruction methods demonstrates the advantage of the EMMML technique over the event circle method, shown in Figure 9.

Figure 9 Simulated image created by the EMML technique.

The camera geometry is the same as shown in Figure 5. The event circle method produces a large background associated with the point source. The effect of this becomes evident in a simulation of the same camera with multiple sources contained in the scene. The scene, illustrated in Figure 10, contains three point sources and a line source (composed of twenty point sources), all at different distances from the camera.

Figure 10 Multiple source simulation geometry.

The reconstructed images can be seen in Figure 11, for the event circle and EMML methods, respectively.

Figure 11 Multiple source simulation images reconstructed by event circle method (left) and EML technique (right).

All of the sources are of equal intensity, therefore the sources should appear with relative strengths inversely proportional to the square of the distance from the camera. Only the EML image recovers this, where the event circle image is dominated by the line source because of the multiple reinforcement caused by its large point spread function.

The experiments were predicted with the FARRAH code assuming a monoenergetic 400keV point source. A sample spectrum of the Se75 source measured by the 10x10x10mm detector during the experimental setup is contained in Figure 12, illustrating three peaks, a 136keV complex, 280keV complex, and a 400keV peak.

Figure 12 Measured Se75 energy spectrum. Note the low energy cutoff.

The simulated count rates were in the range 1.2 to 1.8 counts per second, while the experimental count rates were on the order 1 count per second. A comparison the images produced by the event circle method for the simulation and experiment is contained in Figure 13.

Figure 13 Comparison between simulation (left) and experiment (right).

The experiment image was produced using only the detected events whose energy sum was within 4% of 400keV. The discrepancy in the source location is attributed to the incomplete knowledge of the source location. The source was contained in a 7cm long lead cylinder with open ends. The exact location of the source with respect to the end of the cylinder was not available and a best guess was made.

Although these preliminary results are encouraging, the experiment brought forth some technical issues that must be addressed in further work. The second detector must be shielded from the direct shine of the source to prevent random coincidences from burying the desired signal in background. This is easy in a controlled experiment, but may be more difficult for an unknown scene with high fluxes. A lower level discriminator must be used to reduce unwanted trigger signals to the coincidence unit due to detector noise. This effectively places a low energy limit on the detectors, which is especially significant on the operation of the first plane scattering detector. Since the Compton electron produced from scattering typically contains a small fraction of the photon energy, imaging sources down to 100keV can only be done with scattering detectors that have low noise. For example, we could not resolve an image based on the 280keV Se75 complex from our preliminary experiment. The energy deposited by a Compton electron from a 45 degree scatter for this energy is 40keV. The first plane detector had a noise level measured at 10keV. This noise problem becomes more critical for imaging the 186keV U235 gamma ray, where only 19keV is deposited by the Compton electron for the same scattering angle. In addition, the coplanar grid CdZnTe detectors used for this experiment had slow response times. These detectors had signal rise times on the order of 100ns, which required a coincidence timing window of 3 μ s to capture the timing peak. If detectors with faster signal response can be found, improved coincidence timing could be achieved with associated improvements in the signal to noise ratio.

Plan of Work

To build a successful Compton camera imaging system for SNM will depend on available detector technology. Parameters of particular importance are energy resolution, detector noise, and pulse rise times. These factors have a large influence on the system's capability of imaging in the 100keV to 1MeV range. Noise in the detection system will directly limit the lowest observable energy, which is especially critical in the first plane scattering detector. The range of pulse rise times in the detectors will define the width of the coincidence timing window, directly influencing the image signal to noise ratio. The requirement of a portable instrument strongly implicates designs relying on semiconductor detector technology. These parameters will be measured for available, existing detectors. Once the detector components are selected based on these results, a study using simulation will provide other system parameters, such as optimal detector sizes and separation distances.

Prototype Camera Device:

An optimization study was performed with the FARRAH code to design a Compton camera based on two CdZnTe detectors. The second detector will be mounted a computer controlled xy stage (two degrees of freedom) in order to simulate an array of detectors. A constraint on the optimization was the best spatial resolution attainable with a one count per second count rate, for a 50mCi source at a distance of one foot from the camera. The results of this study suggest a design based on a 8x8x4mm first plane detector and a 10x10x10mm second plane detector provides the best possible resolution of 0.26 radians in the azimuthal direction and 0.11 radians in the polar direction (EMML reconstruction). The camera enclosure and stage system are designed with enough flexibility to accommodate a variety of solid state detector components for future improvements. The electronics and computer for control and readout measurements can be remotely setup and connected via BNC cables. A replacement detector for the first plane made of a low Z material may improve the imaging characteristics of the system. Low Z materials would increase the scatter to absorption ratio, although the interaction rate will decrease due to less electrons per unit volume (7×10^{23} electrons/cm³ for Si and 1.5×10^{24} electrons/cm³ for CdZnTe). We will investigate the use of a silicon based detector technology for this purpose. First plane detector noise is a critical issue in low energy imaging, therefore a successful imaging system must have detectors with very low noise on the order of 1keV. Table 2 summarizes the range of parameters that will be explored in the prototype system development.

Table 2

Evaluate existing, available CdZnTe detectors for noise and rise time.
Evaluate existing, available Si solid state detectors for noise and rise time.
Select optimal detector components from noise, rise time, and simulation results.
Complete and test camera prototype.

The planned date of operation for the prototype is before September 1998. The prototype will be put through a series of experiments which will include highly enriched uranium

and low burnup plutonium sources dispersed in the field of view, see table 3 for an outline of proposed experiments.

Table 3

Experiment	Source Type	Point	Line	Area
1	Pu239	X		
2	Pu239		X	
3	Pu239	X	X	
4	U235	X		
5	U235		X	
6	U235			X
7	U235	X	X	X
8	Pu239+U235	X		
9	Pu239+U235	X	X	

Code Improvements:

Proposed code improvements include using a more complete sampling method via splitting techniques and improved physics. The forcing methods used in the code are not strictly valid. In order to conserve weight, the original particle must be split into two particles, one particle proceeds by forcing the desired event, as before. The other particle must sample a mutually exclusive range and followed to see if it also contributes to the result. This would impact the simulation results for a system with arrays of detector elements in each plane (cross-talk) and for backscattering from the second plane of detectors into the first plane of detectors. If surrounding structural material were included in the simulations, photon scattering out of this material would also impact the result. Corrections to the Klein-Nishina formula will be calculated during code execution based on quantum mechanical techniques using the relativistic impulse model of bound Compton scattering [24]. This will be done to address the effects of small angle and low energy scattering due to electron momentum distributions around the atom. A detailed response function model for CdZnTe, based on first principles, will also be implemented in the code [25].

Summary

Imaging system requirements for the nondestructive assay of special nuclear materials are good energy resolution, large field of view, and system portability. Of existing technology, Compton camera systems based on solid state detector technology provides a superior match to our needs. To this end, we have developed fast simulation capability based on Monte Carlo techniques. The code has been used to design an optimal system, and preliminary experiments have been performed. Based on the results, a prototype system with CdZnTe detector elements will be built in the near future. Other detector technology, which may improve camera performance will be investigated, along with improvements to the Monte Carlo code.

Appendix A

A history in the FARRAH code begins with emission from a source. At this point in code development, all sources are assumed to be point sources, i.e. no self attenuation. Sources are assumed to emit radiation isotropically. The radiation is forced in the range of directions defined by the solid angle of one of the detectors in the first plane. This calculation requires a knowledge of limiting azimuthal and polar angles of the first plane detector from the point of emission. This computation is not trivial and is based on a technique for determining the limiting angles from a point to simple objects such as a circle, cylinder, or a sphere [18]. Instead of using analytical expressions for describing the detectors, a general extension of this technique was developed which defines the convex objects by wire frames and points. This was primarily done to handle orthorhombic shapes of solid state detectors, which we intended to use for this imaging device. The modified pdf for the sampling the azimuthal angle is

$$\hat{f}(\phi) = \frac{1}{\phi_{\max} - \phi_{\min}},$$

where $\phi_{\max}$ and $\phi_{\min}$ are the limiting azimuthal angles of the detector. The associated weight is

$$w = \frac{\phi_{\max} - \phi_{\min}}{2\pi}.$$

After the azimuthal angle is sampled, the modified pdf for sampling the cosine of the polar angle is

$$\hat{f}(\mu) = \frac{1}{\mu_{\max}(\phi) - \mu_{\min}(\phi)},$$

where $\mu_{\max}(\phi)$ and $\mu_{\min}(\phi)$ are cosines of the limiting polar angles $\theta_{\min}$ and $\theta_{\max}$, respectively. The associated weight is

$$w = \frac{\mu_{\max}(\phi) - \mu_{\min}(\phi)}{2}.$$

Once the direction of emission is sampled, a unique path through the detector is defined by this direction and detector's geometry. The gamma ray is forced to have an interaction somewhere along this path. The modified pdf for forcing an interaction within a distance, D is

$$\hat{f}(x) = \frac{\Sigma_t \exp(-\Sigma_t x)}{1 - \exp(-\Sigma_t D)},$$

where Σ_t is the total macroscopic cross section. The associated weight is

$$w = 1 - \exp(-\Sigma_t D).$$

This interaction is forced to be a Compton scattering event by implicit capture. The associated weight for this is

$$w = \frac{\Sigma_{\text{incoh}}}{\Sigma_t},$$

where Σ_{incoh} is the macroscopic incoherent scattering cross section. The scattered gamma ray is then forced in the range of directions defined by the solid angle subtended of one of

the detectors in the second plane. This calculation also requires a knowledge of limiting azimuthal and polar angles of the second plane detector from the point of interaction. The pdf governing this event is the Klein-Nishina formula, but restricted within the range of limiting angles. The azimuthal angle and the cosine of the polar angle are sampled from a restricted range uniform distribution. The weight associated for forcing this interaction to occur is [19]

$$w(\phi, \mu) = \frac{(\phi_{\max} - \phi_{\min})(\mu_{\max}(\phi) - \mu_{\min}(\phi))}{2\pi} f(\mu),$$

where $f(\mu)$ is the Klein-Nishina formula given by [20]

$$f(\mu) = K(\alpha)[\eta^3(\mu) + (\mu^2 - 1)\eta^2(\mu) + \eta(\mu)],$$

with

$$\eta(\mu) = \frac{1}{1 + \alpha(1 - \mu)}$$

$$\alpha = \frac{E}{m_0 c^2}.$$

The parameter α is the initial gamma ray energy over the rest mass of an electron (511keV). The normalization constant is

$$K(\alpha) = \frac{1}{\left[\frac{(\alpha^2 - 2\alpha - 2)}{\alpha^3} \log(1 + 2\alpha) + 2(\alpha^3 + 9\alpha^2 + 8\alpha + 2) / (\alpha^2(1 + 2\alpha)^2) \right]}.$$

Note that this method does not require integrating the Klein-Nishina, only evaluating the function at the sampled value of μ . The exact energy deposited in the detector by the scattered electron is

$$E_{dep} = \frac{\alpha(1 - \mu)E}{1 + \alpha(1 - \mu)}.$$

A simple Gaussian spread model of a detector response function is applied to this deposited energy. Now, the scattered gamma ray must escape the first detector. This is accomplished by a weighting the gamma ray by

$$w = \exp(-\Sigma_t D),$$

where here D is the distance out of the detector and Σ_t is the total cross section evaluated for the energy of the scattered gamma ray. The scattered gamma ray is forced to have an energy deposition interaction (either Compton scatter or photoelectric absorption) in the second plane detector. If a Compton scatter occurs, the scattered gamma ray is allowed to continue in an analog Monte Carlo fashion until it either escapes this detector or is terminated by Russian Roulette. If the weight of a history, w_h drops below a critical value, w_c , then sample a uniform random number, ξ between 0 and 1. If $\xi < w_h/w_c$, then set $w_h = w_c$ and continue the history. If $\xi \geq w_h/w_c$, then set $w_h = 0$ and terminate the history. The energy deposited in the second detector is appropriately recorded and spread by the detector response function. The sequence is repeated from the initial interaction in the first detector to all detectors in the second plane for each history. If there are multiple detectors in the first plane, the next detector is selected and the entire process is repeated.

The issue of multiple Compton scattering in a detector in the first plane before the scattered gamma ray is emitted towards a second plane detector is also addressed. This is embedded in the previous sequence by forcing other Compton scatters before the gamma ray is allowed to escape the first plane detector. The results of allowing 1, 2, 3, and 4 such scatters are calculated, and can be independently viewed from the final result.

The code is not strictly valid in that the technique of splitting is not used each time a given event is forced to occur. The implication for these simulations of a two detector Compton camera is backscattering from the second plane detector into the first plane detector is not addressed. This omission from the code will be corrected in future work.

Appendix B

Block Diagram of Experiment

Signals are digitized by a Keithley/Metrabyte DAS-58/SSH-58 combination with Testpoint software

Equipment List and Settings

Detector 1 Side:

Detector 1

10x10x5mm CdZnTe coplanar grid detector

HV Ortec 459

5kV Detector Bias Supply, -500V

Grid Bias Ortec 459

5kV Detector Bias Supply, +40V

FFA Ortec 579

Fast Filter Amplifier, coarse gain 125, fine gain 1.0, integration time 20ns, differentiation time 50ns, inverted input

CFD Ortec 583

Constant Fraction Discriminator, integral mode, constant fraction mode, lower level discriminator setting 0.26

Delay Ortec 416A

Gate and Delay Generator, 11usec delay range, dial setting 3.0, negative input, delayed marker output

Shaping Amp Ortec 450

Research Amplifier, coarse gain 20, fine gain 10.5, 1us integration and differentiation times, positive normal input, high base line restore, positive 6V output

LG&S Ortec 542	Linear Gate and Stretcher, normal operation, high base line restore
Detector 2 side:	
Detector 2	10x10x10mm CdZnTe coplaner grid detector
HV Canberra 3105	-1500V
Grid Bias Ortec 459	5kV Detector Bias Supply, -20V
FFA Ortec 579	Fast Filter Amplifier, coarse gain 50, fine gain 0.83, integration time 20ns, differentiation time 50ns, non-inverted input
CFD Ortec 583	Constant Fraction Discriminator, integral mode, constant fraction mode, lower level discriminator setting 0.10
Shaping Amp Ortec 673	Spectroscopy Amplifier and Gated Integrator, coarse gain 20, fine gain 0.5, 1us integration and differentiation times, negative input switch, auto base line restore
LG&S Ortec 542	Linear Gate and Stretcher, normal operation, high base line restore
Electronics common to both sides:	
Delay box Ortec DB463	4 channel delay box, 2 channels used by each constant fraction discriminator (127ns of delay for each CFD)
TAC Ortec 567	Time-to-Amplitude Converter/SCA, range set to 100ns with 100x multiplier, internal strobe mode, TAC inhibit mode with SCA window set to 2.0 and SCA lower level set to 2.25, start input from detector 2 side, stop input from detector 1 side, both in anticoincidence mode
LG&S Ortec 542	Linear Gate and Stretcher, normal operation, high base line restore
Digitizer	Keithley/Metrabyte DAS-58/SSH-58 operated by Testpoint software version 3.2, 500kHz sampling rate

Photograph of Compton camera electronics

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