Germanium Strip Detector Compton Telescope Using Three Dimensional Readout

Eric A. Wulf, Bernard F. Phlips *Member, IEEE*, W. Neil Johnson, *Member, IEEE,*
Richard A. Kroeger, *Member, IEEE,* James D. Kurfess, *Member, IEEE,* and Elena I. Novikova

***Abstract*— Compton telescopes using two germanium strip detectors with depth resolution have been demonstrated at the Naval Research Laboratory. Depth resolution allows interactions to be located to less than 1 mm, down from the detector thickness (≈1 cm) with no depth resolution. Depth resolution is shown to improve the imaging resolution of the telescope substantially. Compton images and reconstructed energy spectra are examined using events that interact two or three times with and without full energy losses. These results are compared with simulations of the instrument.**

***Index Terms*— Compton Telescope, Semiconductor Detector, Simulation**

I. Introduction

VARIOUS applications, including astrophysics, medical imaging, and locating fissile materials, require the ability to determine the energy of incident gamma rays and image the gamma ray source. The energy of a gamma ray can be determined with a variety of detectors from a scintillator to a semiconductor with varying sensitivity and energy resolution. Determining the location and energy of a gamma ray source can be done with a multitude of techniques for lower gamma ray energies including collimators, coded apertures, or Compton telescopes with position sensitive detectors. As the gamma ray's energy increases, more material is required to stop it and produce an image. An extension of the Compton technique for imaging that does not require the gamma ray to be completely absorbed in the instrument was explored in [1], [2] and expands the capabilities and sensitivity of a Compton telescope.

A. Compton Telescopes

A Compton telescope, such as COMPTEL [3] on NASA's Gamma Ray Observatory, has to stop the gamma ray completely to get the correct direction cosine of the incoming gamma ray. The gamma ray enters the instrument, Compton scatters in the first detector and the Compton-scattered gamma ray is absorbed completely in the second detector. This type of interaction will be called Two-Compton for this paper. Both detectors need to have position and energy resolution in order to reconstruct an image of the gamma ray source using the Compton scattering formula

$$\cos\theta_1 = 1 + m_e c^2 \left(\frac{1}{E} - \frac{1}{E_1}\right), \tag{1}$$

where θ_1 is the Compton scattering angle of the incident gamma ray, E is the energy of the original gamma ray, and E_1 is the energy of the scattered gamma ray. $E = L_1 + L_2$ where L_1 is the energy deposited at the Compton scattering site and L_2 is the energy deposited when the gamma ray is absorbed. $E_1 = L_2$ when the scattered gamma ray is stopped completely. From θ_1 and the position of the two interactions, a cone can be drawn that includes the direction of the incident gamma ray. The overlap of the cones from multiple events gives the original source position (see Fig. 1). For near field applications, e.g.

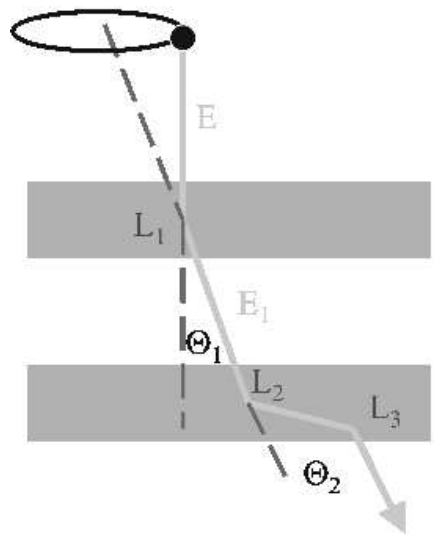

Fig. 1. A cartoon of the experimental setup with 3 interactions (L1, L2, L3) in the two detectors. The source is shown as a large dot on the reconstructed Compton ring. For Two-Compton, imagine the gamma ray stopping at the second interaction point. This experiment only had two detectors so Three-Compton was measured by looking for two interactions in one detector as shown.

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E. A. Wulf is a National Research Council–Naval Research Laboratory Research Associate in Washington, DC 20375 USA (telephone: 202-404-1475, e-mail: wulf@nrl.navy.mil).
B. F. Phlips is with the Naval Research Laboratory, Washington, DC 20375 USA (telephone: 202-767-3572, e-mail: phlips@nrl.navy.mil).
W. N. Johnson is with the Naval Research Laboratory, Washington, DC 20375 USA (telephone: 202-767-6817, e-mail: johnson@ssd5.nrl.navy.mil).
R. A. Kroeger is with the Naval Research Laboratory, Washington, DC 20375 USA (telephone: 202-767-7878, e-mail: kroeger@ssd5.nrl.navy.mil).
J. D. Kurfess is with the Naval Research Laboratory, Washington, DC 20375 USA (telephone: 202-767-3182, e-mail: kurfess@ssd5.nrl.navy.mil).
E. I. Novikova is with George Mason University, Fairfax, VA 22030 USA (email: novikova@ssd5.nrl.navy.mil).

locating fissile materials and medical imaging, the cones are drawn on a plane parallel to the front face of the instrument. To find the location of the source, the distance to this plane must be varied to find the best reconstruction. For astronomy, where photons from a source are parallel to one another, only one reconstruction is done on a sphere at infinity.

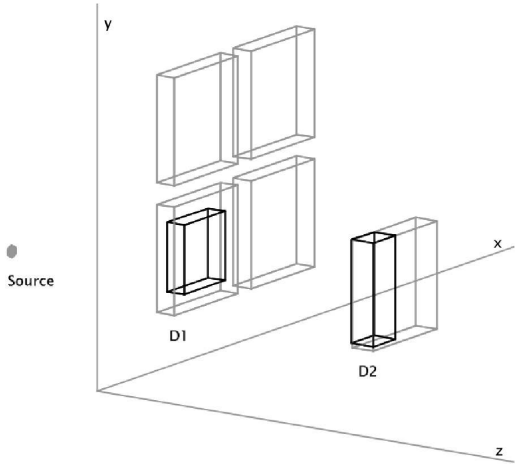


Fig. 2. The geometry of the experimental setup as simulated by GEANT4. D1 is the detector closest to the source which has four crystals in a 2x2 array. D2 is a single crystal shown on the right. The areas shown in black are the sections of the detectors that were instrumented for this experiment.

At higher gamma ray energies, it becomes increasingly difficult to design an instrument capable of stopping the gamma ray completely. Instead, one can use detectors with good position and energy resolution that are thick enough to have the gamma ray Compton scatter two or more times. In 1987, Kamae *et al.* [4], [5] were the first to propose and simulate this idea with an instrument made of multiple layers of silicon detectors with a large scintillation detector surrounding them. The energy of the incident gamma ray was determined from the sum of the energies deposited in all of the detectors and Compton kinematics were used to determine the order of interactions. In 1990, Dogan *et al.* [6] realized that a Compton telescope could determine the position and energy of the gamma ray without stopping the gamma ray completely. One needs only the location of the first three interactions and the energy deposited at the first two interactions. This will be called Three-Compton for this paper. This raises the efficiency by allowing more types of interactions to be used in the reconstruction. The positions of these three interaction sites determine the second Compton scattering angle, θ_2. This angle and the energy deposited at the first and second sites, L_1 and L_2 respectively, yield the original gamma ray energy, E, [1], [2]

$$E = L_1 + \frac{L_2}{2} + \frac{1}{2}\sqrt{L_2^2 + \frac{4m_e c^2 L_2}{1-\cos\theta_2}}. \qquad (2)$$

One can then use Equation 1 with the calculated initial energy and $E_1 = E - L_1$ to determine the first Compton scattering angle. Knowing the original gamma ray energy and Compton scattering angle enables imaging using the same intersecting ring method used in a traditional Compton telescope (see Fig. 1). Reconstruction of the energy and Compton scattering angle using Three-Compton has been shown for ^{88}Y in xenon by Oberlack *et al.* [7].

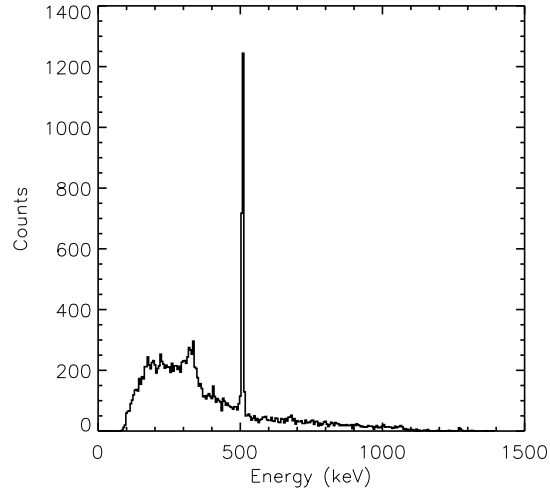


Fig. 3. A spectrum of the total energy deposited in both detectors for events that interacted in both detectors.

It is obvious from Equation 2 that the $\frac{1}{1-\cos\theta_2}$ term is the dominant term for small angles and determination of θ_2 needs to be as accurate as possible. The Compton scattering cross section for high energy gamma rays is dominated by small angle scattering, so good three dimensional position resolution is important to determine θ_2. Thin detectors could be used so that the interaction depth within each detector need not be measured. Thin detectors require many more channels of electronics to achieve the same amount of detector material one would have with thicker detectors. Thicker detectors require depth resolution or a large separation between detectors to determine the scattering angle as accurately as possible. Unfortunately, a large separation between detectors reduces the efficiency of the instrument. Depth resolution is relatively easy to accomplish and has been recently demonstrated for a germanium strip detector [8], but this requires more complex electronics.

There is a limit on the position and energy resolution of an instrument because the Compton scattering is off of electrons that have non-zero momentum [9]. This was recognized as an issue for Compton imaging by Ordonez *et al.* [10] and is called Doppler broadening. It introduces additional uncertainties in the energy and angle of the scattered gamma ray. This effect averaged over all scattering angles for a 200 keV gamma ray is 1.8° in silicon, 2.9° in germanium, and 3.3° in xenon [11]. A Doppler broadening package for the GEANT4 Monte Carlo package [12] was used to simulate this effect. The package is similar to the EGS4 package [13] and was written by R.M. Kippen of Los Alamos National Laboratory.

The Compton telescope works well in the Two-Compton mode (two interactions where the incident gamma ray energy is fully absorbed) for low energies and Three-Compton mode

(three or more interactions where the gamma ray does not have to be stopped) for higher energies. One data set can be taken for both modes and software can be used to select events for each mode. This allows one instrument to span a large energy range.

B. Ordering Algorithms

Ordering the three interactions that make up a Three-Compton event needs to be done properly in order to get a reconstructed image and energy spectrum. This is an area that has been studied multiple times. Kamae *et al.* [4], [5] used an algorithm that calculated the Compton scattering angle from geometry and from the energies deposited and used this to check if the order was correct. This method works when the energy of the gamma ray is fully absorbed and one only needs to know the order to reconstruct the direction cosine. Aprile *et al.* extended the idea of a multiple scattering Compton telescope to liquid xenon and used an ordering algorithm that computes a figure of merit based on the square of the difference between the reconstructed energies from geometry and from the energy deposited in the xenon [14]. Schmid *et al.* expanded this method for use in GRETA where there are high-multiplicity events in germanium detectors [15]. Boggs and Jean [16] also expounded on the algorithm from [14] for multiple layers of germanium strip detectors.

Kroeger *et al.* [17] developed an algorithm to select the most probable order of Three-Compton interactions when the gamma ray is not stopped completely by the instrument. The algorithm took the six different sequences for three interactions and calculated a probability based on Compton scattering cross section and attenuation of the gamma ray traveling through the detector,

$$p_{tot} = \sigma_1(E_1, \theta_1)\sigma_2(E_2, \theta_2)e^{-r_1/t_1}e^{-r2/t_2}, \qquad (3)$$

where p_{tot} is the total probability, σ_1 and σ_2 are the Klein-Nishina calculated cross sections for the first and second interactions, r_1 and r_2 are the distances that the scattered gamma rays traveled in the detector material, and t_1 and t_2 are the attenuation lengths in the detector material for the appropriate gamma ray energies. The correct order is assumed to be the one with the maximum p_{tot}. This algorithm is the one used for this work.

II. Experimental Setup

The gamma ray imaging laboratory at the Naval Research Laboratory has two germanium strip detectors from Eurisys Mesures in separate cryostats. Three detectors would improve the setup for exploring Three-Compton but that experiment will have to wait for the acquisition of a third detector and more electronics. Instead, events that interacted once in one detector and twice in the other were used for Three-Compton (see Fig. 1). The case of three detectors was simulated to explore what will be possible with a third detector, see Sec. III-C.

The detector on the left in Fig. 2 (referred to as D1) has four identical crystals daisy chained into a 2x2 matrix [18].

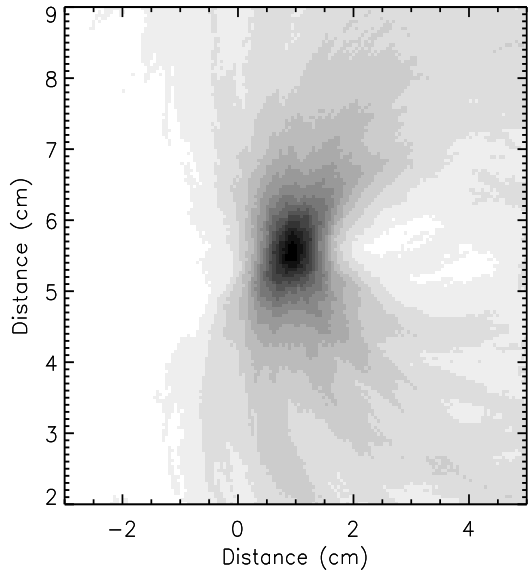


Fig. 4. A Compton ring image of the events from ^{22}Na that interacted once in each detector and whose energy summed to 511 keV, i.e. Two-Compton.

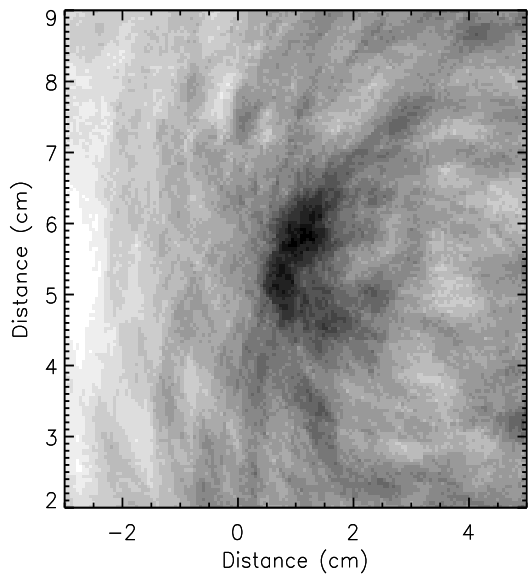
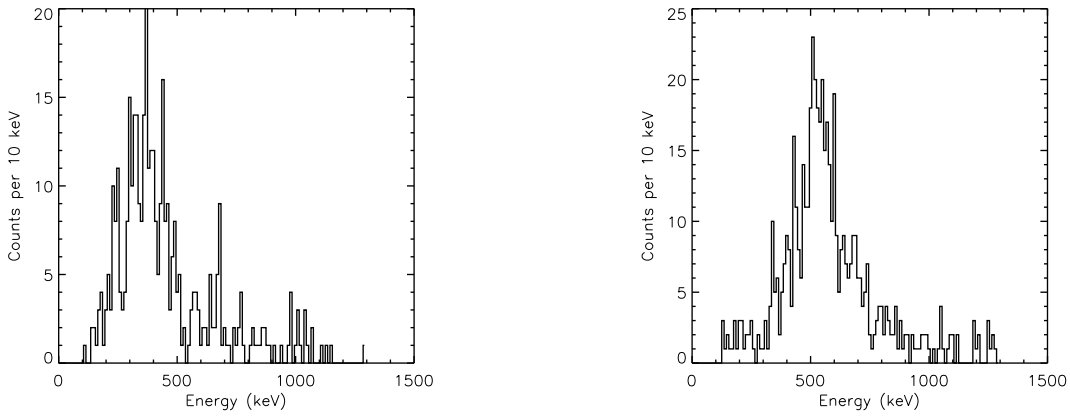


Fig. 5. A Compton ring image of the events from ^{22}Na that interacted once in one detector and twice in the other detector, i.e. Three-Compton.

These four crystals are all 25x25 orthogonal strip detectors approximately 1 cm thick with 2mm strip pitch. The detector on the right in Fig. 2 (referred to as D2) is a 25x25 orthogonal germanium strip detector with 2mm strip pitch and approximately 1 cm in thickness [19]. Boron implanted contacts are used on one side and lithium diffused contacts on the other. This detector was used to show three dimensional readout of a detector [8], [20].

Orthogonal strips on the front and rear faces of the crystal



(a) Original with Photopeak Removed

(b) Reconstructed

Fig. 6. For events that interacted three times, in (a) is the original summed spectrum with 511 keV events removed. In (b) is the reconstructed energy spectrum using the Three-Compton technique.

allow germanium strip detectors to locate a gamma-ray interaction in two dimensions accurate to the width of the strips. A gamma ray interacts in the crystal and its position is determined by the intersection of the triggered strips on opposite sides of the detector. The depth of the interaction is determined by looking at the timing difference between charge collection of holes on one side of the detector and electrons on the other. The interaction depth is nearly proportional to this time difference and has been measured to be less than 0.5 mm at 122 keV [8].

The D1 detector had one crystal in the 2x2 matrix partially instrumented. The other channels of the other crystals were ignored in this experiment but could be used in the future when more electronics are available. The D2 detector has 24 of the boron strips and 10 of the lithium strips instrumented. The electronics included the NRL NIM timing and shaping electronics [8] and CAMAC Time to Digital Converters (TDCs) and Analog to Digital Converters (ADCs) for all 66 channels.

The detectors were placed with D1 closest to the source and D2 10.2 cm behind it. The separation between detectors was close to the minimum allowed by the cryostats of the two detectors. To determine the exact orientation of the detectors with respect to each other, a position table scanned a ^{57}Co source, collimated to a fan beam, across the x and y dimensions of the detectors. A ^{133}Ba source collimated to a fan beam and mounted on a position table with a 20 cm range scanned the z dimension starting at the front edge of D1 and ending at the rear edge of D2. This gave the relative distance between the two detectors and checked that the depth information for each detector was being properly measured. From this it was determined that the crystal in D1 was 0.9 cm thick and D2 was 1.1 cm thick. Depth determination was found to work the same in D1 as it had in previous work on D2 [8]. A geometry with the detectors closer together would have improved the efficiency and the range of accepted Compton scattering angles but would have increased the effect of the position uncertainty due to the strip pitch.

III. Results

A. Imaging of a ^{22}Na Source

^{22}Na decays by emitting a β^+ and a 1275 keV gamma ray. The β^+ annihilates and produces back to back 511 keV gamma rays. A 10 μCi source was placed 7.6 cm from the front face of the large detector.

The data acquisition system required a coincidence between the two detectors to record the event. To select Two-Compton events, events that interacted in both detectors once were selected in software. A spectrum of these events is shown in Fig. 3. Because this spectrum was taken in coincidence and summed over both detectors, one will notice the prominent 511 keV peak and the diminished Compton edge. Selecting the Two-Compton events that summed to 511 $\pm$ 10 keV and drawing Compton rings at a plane 7.6 cm from the front face of the first detector yielded the ring image shown in Fig. 4. The full width at half-maximum (FWHM) of the ring image is 0.9 cm for this ^{22}Na source that is 0.5 cm in diameter. This corresponds to an angular resolution of 5.0 $\pm$ 0.2° (the deconvolution required to obtain this result is described in Sec. III-C).

Selecting events that interacted in one detector once and the other twice yields events for Three-Compton. There are nearly 2.7 times more Two-Compton events than Three-Compton events. This number does not truly represent the ratio between Two-Compton and Three-Compton events because it is difficult to determine if the events selected for Two-Compton and Three-Compton are real or background events. For the Three-Compton events, summing the energy deposited in each detector shows that there are events that sum to 511 keV. Taking the events whose energy sum to less than 511 keV, i.e. those gamma rays

that were not stopped completely in the instrument, and producing a Three-Compton image shows a point at the same position as the Two-Compton image. The Three-Compton events that sum to 511 keV, gamma rays that were stopped completely, produce an image at the same point. Finally, analyzing the events that had total deposited energy greater than 511 keV, presumably from the 1275 keV gamma ray or a 1275 keV and 511 keV gamma ray in coincidence, also produced an image at the same point. All the Three-Compton events imaged together produces the image shown in Fig. 5. This corresponds to an angular resolution of 11 $\pm$ 0.3°.

For this work, the ordering algorithm of Kroeger *et al.* [17], which uses the cross section and attenuation probabilities, was used. The first interaction was assumed to always be in D1, the detector closest to the source. The case where the gamma ray interacted in D1 then D2 and then scattered back to D1 was assumed to have zero probability to reduce the number of sequences to check. Events that were non-physical, based on the calculated Compton scattering angle, were not considered. This ordering algorithm works at 511 keV as shown by a reconstructed image with a point at the correct location in Fig. 5. The blurring of this image could be due to a number of factors. Ordering the gamma rays is a more difficult task below 1 MeV as was shown in [17]. 511 keV is a particularly bad energy for reconstruction because at least two candidate sequences have nearly equal probabilities over a wide range of scatter angles. Another factor that contributes to the blurring of the image could be misalignments in the system. The scanning of the instrument with the radioactive source would not have shown rotations of the detectors with respect to each other.

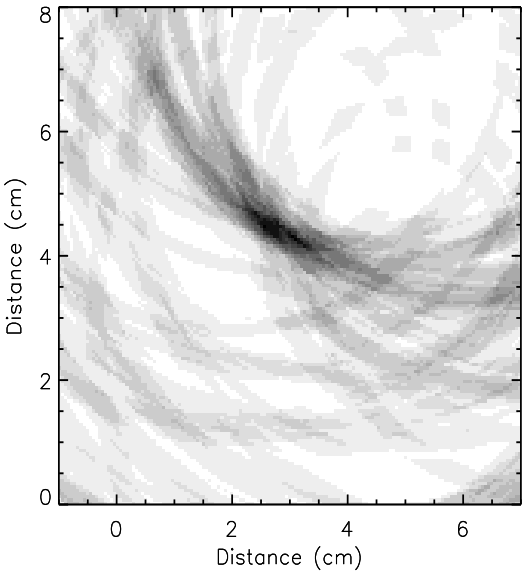


Fig. 7. The Two-Compton image for ^{60}Co is shown. The image is smeared due to low statistics because there are 30 times more Three-Compton than Two-Compton events. One can see the preferential scattering angle due to the instrument geometry.

The Three-Compton technique can reconstruct the original gamma ray energy. A spectrum of Three-Compton events that do not sum to 511 keV is shown in Fig. 6(a) and after reconstruction using Equation 2 in Fig. 6(b). Even without a peak at the photopeak energy in the original events the Three-Compton method produces a peak at 511 keV with a high energy tail. A number of the events did not reconstruct to the proper energy due to getting the order of interactions wrong and because some events were not originally from 511 keV gamma rays. The high energy tail on the 511 keV peak was also seen in current Monte Carlo simulations and in simulations of lower energy gamma rays and is due to misordered events [17]. Another issue is that the path length between events in the same detector is often 5 mm or less. Requiring that the path length be 1 cm or more reduces the statistics but also improves the reconstructed energy spectrum. The longer path length allows the Compton scattering angle to be determined more accurately and should be more helpful at higher energies. This requirement demonstrates a situation similar to a real instrument where multiple detectors, and therefore interactions, are typically separated by more than 1 cm. In fact, for a 511 keV instrument with multiple germanium detectors one should be able to attain a reconstructed energy resolution on the order of 30 keV FWHM [17], limited by Doppler broadening and pixel size, as compared to the current energy resolution of 130 $\pm$ 10 keV FWHM.

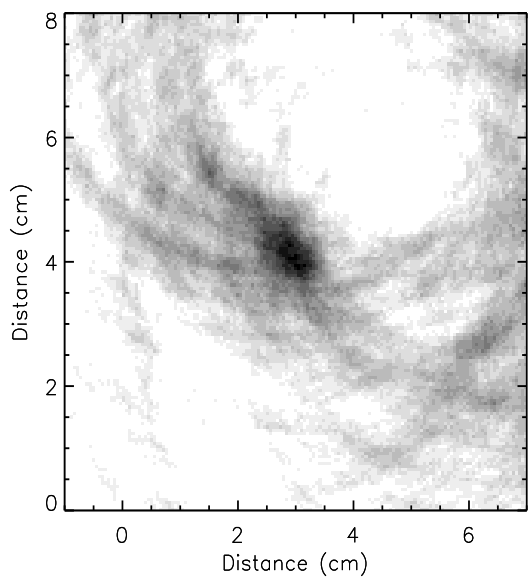


Fig. 8. The Compton ring image from the Three-Compton technique for ^{60}Co. The 1173 and 1333 keV energy lines image to the same point.

For this experimental configuration, depth information is important for Three-Compton imaging but not as important for Two-Compton. This is due to the large dependence on position information in the Three-Compton formula (Equation 2), particularly for forward scattering. Eliminating the depth information smears and shifts the Two-Compton ring image

slightly, but for Three-Compton with no depth information the image shows no reconstructed point.

B. Imaging of a ^{60}Co Source

^{60}Co decays by emitting 1173 and 1333 keV gamma rays. A 10 μCi source was placed 6.5 cm from the front of the D1 detector. Choosing Three-Compton events yielded 16 times more events than for Two-Compton at these energies. Making a traditional Two-Compton image of the ^{60}Co yielded an image with an angular resolution of $4.5 \pm 0.2°$ (see Fig. 7). The Three-Compton image shows a well defined point ($7.4 \pm 0.3°$ angular resolution) that was at the same position whether events came from the 1173 or 1333 keV line (see Fig. 8). This proves that the Three-Compton technique can image and it helps to illustrate the usefulness of the Three-Compton technique for gamma rays that would otherwise be difficult to stop completely.

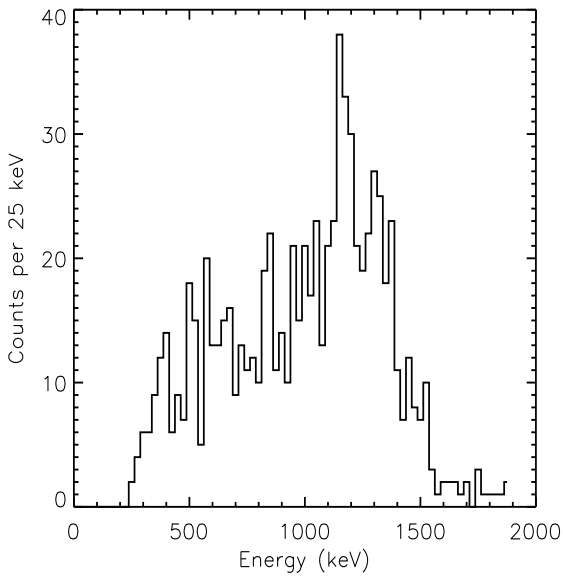


Fig. 9. A reconstructed energy spectrum of Three-Compton events from ^{60}Co where the interactions are separated by at least 1 cm.

Reconstructing the energy spectrum for these energies is more difficult with this geometry. Only 2% of the Three-Compton events stopped the gamma ray completely in the instrument so any peak must be due to correct reconstruction. Reconstructing the energy spectrum of all Three-Compton events collected shows small peaks at 1173 and 1333 keV with an energy resolution of 140 ± 10 keV. However, when events are selected that traveled at least 1 cm between interactions, the reconstructed spectrum (see Fig. 9) shows a peak at both 1173 keV and 1333 keV. This is due to the large fraction of events with small separation, and therefore poor resolution of the critical angle, θ_2, in Equation 2. The geometry of the system with only two detectors is far from ideal but does demonstrate the power of this technique.

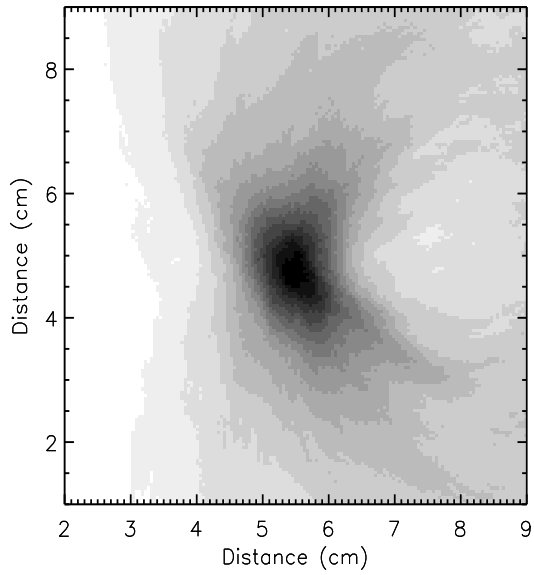


Fig. 10. A Compton ring image of GEANT4 simulated events from a 0.5 cm diameter 511 keV source that interacted once in each of three crystals i.e. Three-Compton.

C. GEANT4 Monte Carlo

A GEANT4 Monte Carlo simulation [12] was done to simulate the two germanium crystals used in this experiment. Dead material and shielding materials were ignored for this simulation. The simulations were run with and without Doppler broadening [13] and energy resolution and pixelization effects were added during the analysis of the simulated data. The geometry of the simulation is shown in Fig. 2. The simulation recorded both Two-Compton and Three-Compton events with information about the correct order of interactions. The data sets from the simulation were reconstructed using the same ordering algorithm, energy reconstruction, and imaging code as the real data. A 0.5 cm diameter source was simulated emitting either 511 keV or 1173 keV gamma rays.

A deconvolution was performed to obtain the angular resolution of the instrument. The reconstructed ring image of the simulation with no Doppler broadening and perfect energy and position resolution was used to define the response of the instrument at a particular gamma ray energy and for either Two- or Three-Compton. Next, the width of the ring image, whose angular resolution is to be determined, is measured. The simulated response of the detector is then convolved with gaussians of varying width. The result of the convolution that has the correct width is used to calculate the angular resolution.

All of the data from the experiment and from the simulations is summarized in Table I. The Two-Compton angular resolution shows good agreement between experiment and simulation. One can see that Doppler broadening widens the angular resolution to $> 3°$ for this geometry and that the 2 keV energy resolution has little effect on the angular resolution. Adding the effects of 1 or 2 mm pixelization in x and y and 0.5 mm

TABLE I

SUMMARY OF ANGULAR RESOLUTION IN DEGREES AND ENERGY RESOLUTION IN KEV FOR VARIOUS SIMULATIONS. RESULTS ARE GIVEN FOR 511 KEV AND 1173 KEV GAMMA RAYS. TWO DIFFERENT GEOMETRIES ARE EXAMINED FOR THREE-COMPTON, ONE WITH TWO CRYSTALS LIKE THE CURRENT EXPERIMENT AND ANOTHER WITH A THIRD CRYSTAL.

Type of Monte Carlo Simulation	Two-Compton		Three-Compton (2 Crystals)				Three-Compton (3 Crystals)			
	Angular (Deg)		Angular (Deg)		Energy (keV)		Angular (Deg)		Energy (keV)	
	511	1173	511	1173	511	1173	511	1173	511	1173
Doppler	4.4	3.3	5.9	2.5	16.7	16.5	7.8	4.1	46.5	72.7
Doppler+2keV	4.5	3.3	5.9	2.5	18.6	18.2	7.9	4.2	53.8	72.7
Doppler+2keV+1mm	4.7	3.8	9.8	7.0	93.4	104	8.4	5.0	56.4	92.6
Doppler+2keV+2mm	5.3	4.3	11	7.1	95.8	106	8.8	6.0	67.3	122
Measured	5.0	4.5	11	7.4	130	140	–	–	–	–

resolution in z, reduces the angular resolution further. The large angular resolution is due to the geometry only accepting small Compton scattering angles and from the large strip pitch of D1 and D2. Larger detectors with the detectors closer together and with smaller strip pitch would increase the angular acceptance and decrease the effects of Doppler broadening and pixelization. 1173 keV gamma rays are more likely to forward scatter than 511 keV and are therefore affected more by pixelization.

The Three-Compton angular resolution for the experimental setup, i.e. two crystals, shows good agreement with the experimental data. Doppler broadening again reduces the angular resolution and energy resolution has little effect. Pixelization has a much larger effect on the angular resolution than it did for Two-Compton. This result is not surprising because position resolution is very important for determining the energy of the incident gamma ray as is evident from energy resolution shown in Table I. This is caused by uncertainties in the critical angle, θ_2, in Equation 2 so that the original gamma ray energy is not well determined. The scattered 1173 keV gamma rays are also easier to order correctly because they are much more forward peaked. The energy resolution measured by experiment are larger than expected from the simulation which needs to be explored further.

A second geometry was studied that had a third crystal with the same physical dimensions as D1 and was placed 10.2 cm behind D2. Doppler broadening reduces the angular resolution by a much larger extent than for two crystals, but the pixelization is not as large an effect due to the greater path length between interactions. The ordering algorithm also works better as can be seen by comparing the amount of noise around the central feature in Fig. 10, which is simulated for three crystals, to Fig. 5, which was measured using two crystals.

IV. CONCLUSION

The Three-Compton technique is able to produce images that are comparable to those of the traditional Two-Compton method especially at energies over 1 MeV. The Two-Compton and Three-Compton methods can be used to complement each other as their efficiencies change for different energies and instrument configurations. The ability to reconstruct the gamma ray's position and energy without stopping it completely will enable the construction of Compton telescopes for high energy gamma rays that are smaller than if they had to stop the gamma ray. GEANT4 simulations of the system agree with actual measurements of the angular resolution and do a reasonable job of predicting the energy resolution. This will allow the performance of an instrument to be maximized before the instrument is constructed.

The current system was designed to demonstrate the concept of Three-Compton in germanium with the resources available and its position and energy resolution are not a true reflection what can be achieved with a well designed Compton telescope. The small distance between events and the small range of Compton scattering angles accepted reduced the ability of the instrument to reconstruct the Compton rings and original gamma ray energy. Instrumenting three detectors and having the detectors inside of one cryostat where their orientations are known would improve the abilities of the telescope. Reducing the strip pitch would also help to increase the resolution closer to the limits imposed by Doppler broadening.

Demonstrating a Compton telescope constructed from silicon strip detectors will allow exploration of the effects of Doppler broadening because Doppler broadening reduces with decreasing atomic number. Based on GEANT4 simulations, an instrument built out of 95x95 mm silicon strip detectors 3mm thick arranged in layers of 3x3 detectors with 8 layers, a strip pitch and depth resolution of 0.5 mm, and an energy resolution of 3 keV, will have a reconstructed energy resolution of 10 keV and a angular resolution of 2.2° for an 847 keV gamma ray. Making a large area instrument with many layers of detectors should allow efficiencies on the order of 17% for Three-Compton interactions in germanium detectors and 5% for Two-Compton for 1 MeV incident gamma rays [17].

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REFERENCES

[1] N. Dogan and D. K. Wehe, "Optimization and angular resolution calculations for a multiple compton scatter camera," in *1993 IEEE Nucl. Sci. Symp. and Med. Imaging Conf. Record*, 1994, pp. 269–273.

[2] J. D. Kurfess, W. N. Johnson, R. A. Kroeger, and B. F. Phlips, "Considerations for the next compton telescope mission," in *AIP Conference Proceedings*, vol. 510, 2000, p. 710.

[3] V. Schonfelder, H. Aarts, K. Bennett, H. Deboer, J. Clear, W. Collmar, A. Connors, A. Deerenberg, R. Diehl, A. Vondordrecht, J. W. Denherder, W. Hermsen, M. Kippen, L. Kuiper, G. Lichti, J. Lockwood, J. MacRi, M. McConnell, D. Morris, R. Much, J. Ryan, G. Simpson, M. Snelling, G. Stacy, H. Steinle, A. Strong, B. N. Swanenburg, B. Taylor, C. Devries, and C. Winkler, "Instrument description and performance of the imaging gamma-ray telescope comptel aboard the compton gamma-ray observatory," *Astrophys. J. Suppl. Ser.*, vol. 86, pp. 657–692, 1993.

[4] T. Kamae, R. Enomoto, and N. Hanada, "A new method to measure energy, direction, and polarization of gamma-rays," *Nuc. Inst. Meth. A*, vol. 260, pp. 254–257, 1987.

[5] T. Kamae, N. Hanada, and R. Enomoto, "Prototype design of multiple compton gamma-ray camera," *IEEE Trans. Nucl. Sci.*, vol. 35, pp. 352–355, 1988.

[6] N. Dogan, D. K. Wehe, and G. F. Knoll, "Multiple compton-scattering gamma-ray imaging camera," *Nucl. Inst. Meth. A*, vol. 299, pp. 501–506, 1990.

[7] U. Oberlack, E. Aprile, A. Curioni, V. Egorov, and K. Giboni, "A compton scattering sequence reconstruction algorithm for the liquid xenon gamma-ray imaging telescope (lxegrit)," in *2000 Astronomical Telescopes and Instrumentation, SPIE*, vol. 4141, 2000, pp. 168–177.

[8] E. A. Wulf, J. Ampe, W. N. Johnson, R. A. Kroeger, J. D. Kurfess, and B. F. Phlips, "Depth measurement in a germanium strip detector," *IEEE Trans. Nucl. Sci.*, vol. 49, pp. 1876–1880, August 2002.

[9] J. DuMond, "Compton modified fine structure and its relation to the electron theory of solid bodies," *Phys. Rev.*, vol. 33, pp. 643–648, 1929.

[10] C. Ordonez, A. Bolozdynya, and W. Chang, "Doppler broadening of energy spectra in compton cameras," in *1997 IEEE Nucl. Sci. Symp.*, vol. 2, 1998, pp. 1361–1365.

[11] A. Zoglauer and G. Kanbach, "Doppler broadening as a lower limit to the angular resolution of next generation compton telescopes," in *2002 Astronomical Telescopes and Instrumentation, SPIE*, 2002, p. to be published.

[12] K. Amako, "Present status of geant4," *Nucl. Inst. Meth. A*, vol. 453, pp. 455–460, 2000.

[13] Y. Namito, S. Ban, and H. Hirayama, "Implementation of the doppler broadening of a compton-scattered photon into the egs4 code," *Nucl. Inst. Meth. A*, vol. 349, pp. 489–494, 1994.

[14] E. Aprile, A. Bolotnikov, D. Chen, and R. Mukherjee, "A liquid xenon imaging telescope for gamma-ray astrophysics - design and expected performance," *Nucl. Phys. B*, pp. 279–286, 1993.

[15] G. J. Schmid, M. A. Deleplanque, I. Y. Lee, F. S. Stephens, K. Vetter, R. M. Clark, R. M. Diamond, P. Fallon, A. O. Macchiavelli, and R. W. MacLeod, "A gamma-ray tracking algorithm for the greta spectrometer (vol 430, pg 69, 1999)," *Nucl. Inst. Meth. A*, vol. 434, pp. 481–481, 1999.

[16] S. E. Boggs and P. Jean, "Event reconstruction in high resolution compton telescopes," *Astron. Astrophys. Suppl. Ser.*, vol. 145, pp. 311–321, 2000.

[17] R. A. Kroeger, W. N. Johnson, J. D. Kurfess, B. F. Phlips, and E. A. Wulf, "Three-compton telescope: theory, simulations, and performance," *IEEE Trans. Nucl. Sci.*, vol. 49, pp. 1887–1892, August 2002.

[18] B. F. Phlips, W. N. Johnson, R. A. Kroeger, J. D. Kurfess, G. Phillips, E. A. Wulf, and P. N. Luke, "Development of germanium strip detectors for environmental remediation," *IEEE Trans. Nucl. Sci.*, vol. 49, pp. 597–600, April 2002.

[19] R. A. Kroeger, W. N. Johnson, J. D. Kurfess, R. L. Kinzer, N. Gehrels, S. E. Inderhees, B. Phlips, and B. Graham, "Spatial resolution and imaging of gamma-rays with germanium strip detectors," in *SPIE EUV, X-Ray, and Gamma-Ray Instrumentation for Astronomy VI*, vol. 2518, Nov 1995, pp. 236–243.

[20] M. Momayezi, W. K. Warburton, and R. Kroeger, "Position resolution in a ge-strip detector," in *SPIE Conf. Proc.*, vol. 3768, 1999, pp. 530–537.