Performance of a Compton Telescope using Position-Sensitive Germanium Detectors

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ABSTRACT

We describe the use of position sensitive planar germanium detectors in a Compton telescope/camera. This Compton telescope achieves the very good energy resolution ($\Delta E\textit{total}$ < 4 keV) associated with germanium detectors and good position resolution (2 mm). By combining a 25 x 25 strip (2 mm pitch) detector with a 5 x 5 strip detector (9 mm pitch), we created a telescope with 625 x 25 pixel combinations. Using this detector pair, we have reconstructed positions with an angular resolution of ~ 1 degree FWHM and 15 arcminute centroiding. Point sources are identified with less than 100 full energy events with simple image reconstruction. The angular resolution is currently limited by the uncertainty in the absolute position of the detectors and the size of the second detector pixels. We show the expected angular resolution when the pixel size no longer dominates the angular resolution and discuss proposed applications.

INTRODUCTION

The imaging of photon sources at MeV energies is of relatively poor spatial resolution when compared to imaging at lower energies or even very high energies. At low energies, photons interact by the photoelectric effect and stop esentially at a point. At very high energies (>10's of MeV) photons pair produce and are imaged using standard methods of particle detection. At MeV energies, most photons Compton scatter, and have a stopping range that is comparable to the size of typical detectors (cm's). It therefore becomes impractical to construct direct imaging detectors systems with thick masks, pin-hole or coded aperture, that have hundreds of pixels a side if each pixel has to be a few centimeters in size. Coded aperture telescopes have the additional weakness of losing sensitivity as the angular size of a source grows, i.e. not being able to image diffuse sources. The Compton Telescope (or Compton camera) has emerged as a convenient imaging method in this energy range.

In a Compton telescope, two separate layers of detector are used (see figure 1). An incoming photon Compton scatters in the first detector (D1) and is absorbed in the second detector (D2). If the energy and the position of the interactions in both detectors are measured, then one can calculate a cone of angles from which the photon could have originated. The origin of a single photon can only be constrained to a ring of possible directions, but with multiple photons the rings will only cross at the true source position. This imaging method does not require heavy masks and potentially has a very large field of view. Unfortunately, since a coincidence between two detectors with limited efficiency is required, the overall system efficiency is rather low, typically ~3% for a system with the detector planes of the same size as their separation.

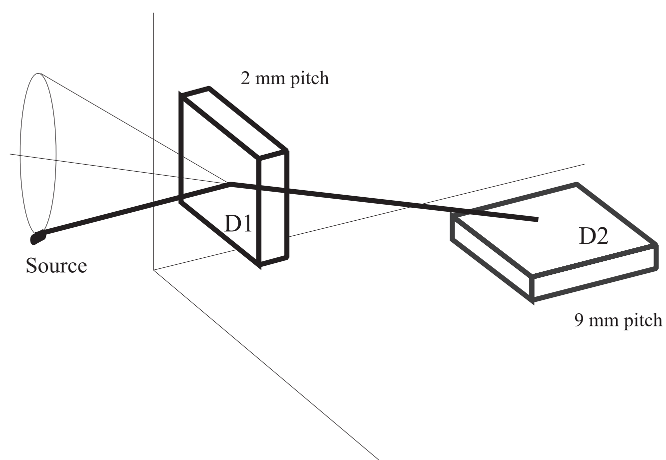

Fig. 1: Sketch of the geometry used for the germanium Compton telescope experiment.The two detectors are at 90 degrees to each other and have pixels of different size.

A Compton telescope is currently flying on the Compton Gamma Ray Observatory[1] and various groups are

[1]Schonfelder, V. et al., 1993, Astron. Astrophys. Supp. 97, 657

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testing laboratory versions[2,3,4] These systems tend to consist of poor energy resolution detectors (NaI or liquid scintillator) or have very few position pixels. We address both the energy and position resolution issues by using position-sensitive germanium strip detectors with ~2 mm position resolution and ~2 keV energy resolution[5].

MEASUREMENTS

We currently are testing two position sensitive germanium detectors. One has twenty five 2 mm strips orthogonally on each side of the crystal, the other has five 9 mm strips on each side. As shown in figure 1, the 25x25 strip detector is positioned vertically in a cryostat whereas the the 5x5 strip detector is horizontal. We operate the detectors in a telescope mode with the the vertical detector 40-150 cm in front of the horizontal detector, creating 625x25 pixel combinations.

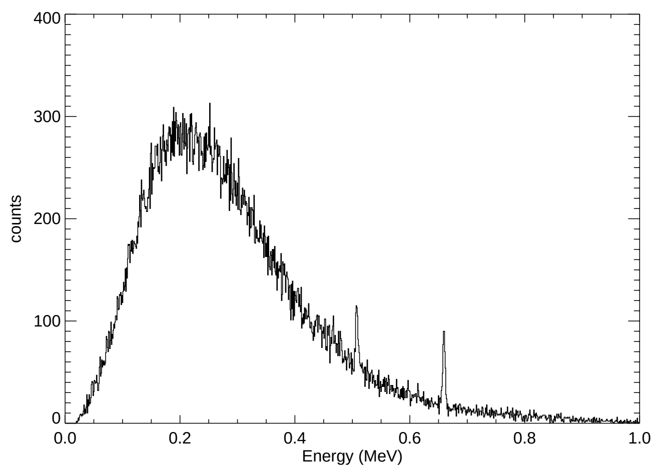

Fig. 2: Energy spectrum for the summed energy deposited in the two detectors for all coincidences. A ^{22}Na and a ^{137}Cs source were in front of the detectors.

Figure 2 shows the summed energy spectrum for detected coincidences. The excellent spectroscopy of germanium detectors is preserved (ΔE_{total} ~ 3.5 keV) and the narrow lines are clearly visible. The energy of the incoming photon does not have to be assumed as in some Compton telescopes. One can choose a line and image the full energy photons. The dark point in figure 3 shows the image of a ^{137}Cs source reconstructed on a plane 8 cm in front of the D1 plane. The image was created with less than 100 full energy photons by generating the sum of all the back-projected rings. The image was reconstructed on planes at various depths and the source-detector distance was obtained by finding the plane with the largest number of counts in a set of pixels (in focus). No further image processing techniques were applied. This method allows one to position the depth of a near-field object to ~1 cm. The lower set of curves in figure 3 is from another source that is "out of focus" by 2.5 cm.

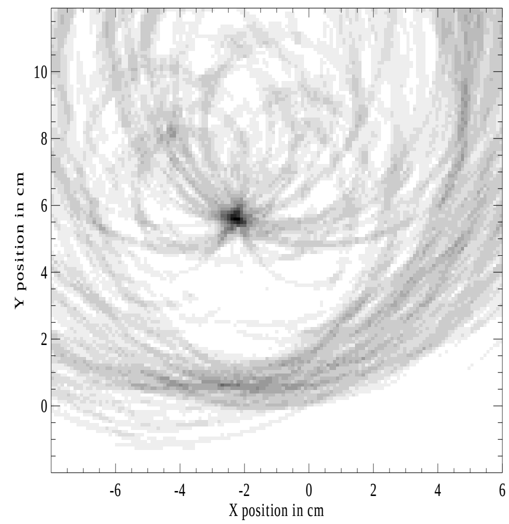

Fig. 3: Image of a Cs source when the two germanium detectors are separated by 45 cm and the source is 8 cm in front of the first detector. Only events with total energy of the photopeak were imaged. A second "out of focus" source can be seen in the lower part of the figure

When the source position is within the direct field of view of the two detectors, rings cross the source location from all directions. However, when the source is outside the direct field of view, only a limited set of rings are possible. The rings produce an image that is narrow in one direction but very wide in the perpendicular direction. Figure 4a shows the image of a source when the detectors are separated by ~130 cm and there is virtually no direct field of view. By expanding to an array of detectors in D1 and D2, rings from more directions can be imaged and the point-like image recovered. Figure 4b is the image generated using four different detector geometry combinations, as would be seen by a system consisting of 4 detectors in plane D1 and one detector in plane D2. The size of the source image is ~2.5 cm FWHM imaged onto a plane 130 cm in front of D1, with centroiding capability to better than 0.5 cm. This performance is equivalent to 15 arc minute angular resolution for sources far away. The images in figure 4 are from the ^{137}Cs peak of figure 2. A similar image can be reconstructed for the ^{22}Na line in a plane 30 cm from the detectors. The angular resolution is currently limited by some uncertainty in the absolute position of the germanium crystals within the cryostats, the inaccuracy in moving the detectors when simulating an

[2] Martin, J. B. et al., 1993, IEEE Trans. Nucl. Sci. NS-40, no. 4, 972
[3] King, S. E. et al., 1994, Nucl. Instr. and Meth. In Phys. Res A 353, 320.
[4] Ait-Ouamer, F. et al., 1990, IEEE Trans. Nucl. Sci. 37, 535
[5] Inderhees, S. E. et al., 1995, these proceedings

array, and mostly the size of the pixels in the D2 plane (9 x 9 x 11 mm voxels).

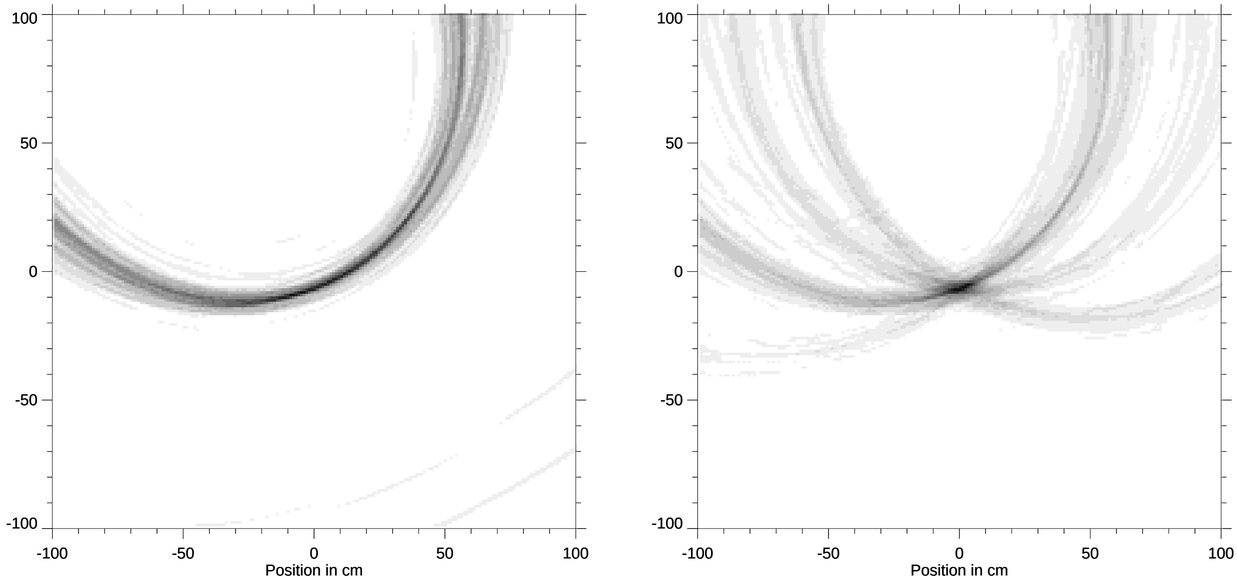

Fig. 4: Images of a Cs source when the two germanium detectors are separated by 130 cm. Figure 4a, on the left, show the event ring sum for one detector pair combination. Figure 4b, on the right, shows the event ring sum for four detector pair combinations.

DISCUSSION

We have demonstrated a Compton telescope with excellent energy resolution ($\Delta E/E < 0.5\%$ at 662 keV) and position resolution (~1 degree FWHM). The angular resolution can be improved by using detectors with small pixels for both the D1 and D2 plane. To that end we are currently developing individually packaged germanum strip detectors. These detectors could then conveniently be handled separately and arrays of them placed into a common cryostat of any desired geometry. We expect to have a 2x2 array of detectors with 2mm position resolution in the next 6 months to replace the current 9 mm pixel detector.

Figure 5 displays the expected angular resolution for such a telescope when the detectors are separated by 1 meter. This capability combined with the energy resolution could find applications in near field imaging, such as medical imaging[6]. and radioactive waste barrel imaging. A medical imaging system, either for PET or SPECT, would have the detector separation be somewhat smaller. For waste barrel imaging, a small Compton camera would provide clear isotopic information by identification of the narrow lines and accurate positioning of the active material within a barrel.

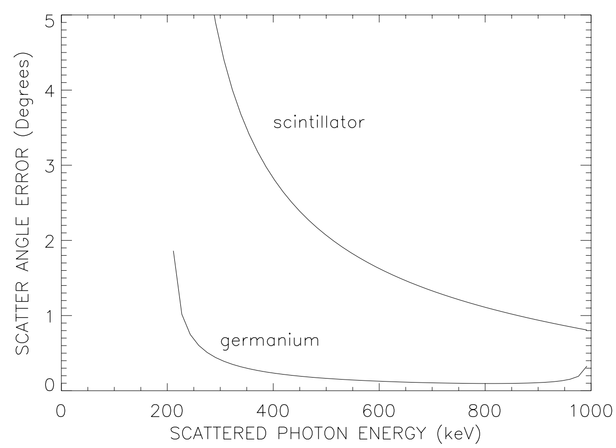

Fig. 5: Error in the reconstructed scatter angle versus scattered photon energy for a 1 MeV incoming photon. The error is due to the energy resolution of the detector, NaI for the upper curve, germanium for the lower curve.

Another application is in gamma ray astrophysics, where a 1 square meter Compton telescope would improve the narrow line sensitivity by a factor of 20 to 50 over ESA's planned INTEGRAL mission[7], with a 3 sigma sensitivity down to $\sim 10^{-7}\ \gamma cm^{-2} s^{-1}$. The ATHENA

[6]McKissen, J. E. et al., 1995, these proceedings

[7]Bergeson-Willis, S. et al., 1993, INTEGRAL Report on the phase A study

concept[8], a proposed Compton telescope mission would provide high spectral and spatial resolution over a broad field of view from 300 keV to 10 MeV. It would consist of 2 layers of 1 cm thick detectors as a D1 plane and six layers of the same detectors for a D2 layer. By adding a coded aperture mask on top of the Compton telescope, the D1 plane can also function as a hard X-ray imaging camera from 10 keV to 200 keV with an arc minute imaging capabilitiy over a ~15 degree field of view (see figure 6).

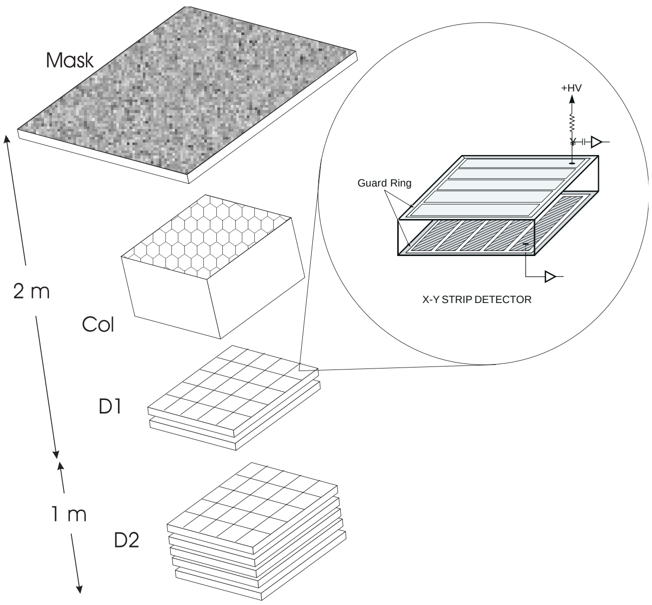

Fig. 6: Conceptual diagram of the combined coded-aperture imager and Compton telescope. The Compton telescope consists of two detector planes (D1 and D2) ~1m apart. A coded aperture is placed ~2m above the top detector plane, which forms the coded aperture imager using the top layer of D1. A coarse collimator just above the D1 layer restricts the field of view for the imager.

ATHENA would be able to image objects like the ^{26}Al line (1809 keV) in the Vela supernova remnant (see figure 7) and compare the ^{26}Al distribution with the lower X-ray emission maps. It would map the galaxy at energies corresponding to lines from positron annihilation, ^{60}Fe, ^{44}Ti, ^{12}C and ^{16}O excited states, and ^{56}Fe resulting from supernovae remnants and cosmic ray spallations. This capability would allow one to test the explosive nucleosynthesis models for galactic novae through obervations of prompt and long lived radioactivities. It would also determine the surface gravitational fields of neutron stars by redshift measurements of nuclear line emission and thereby constrain the equation of state of neutron star material.

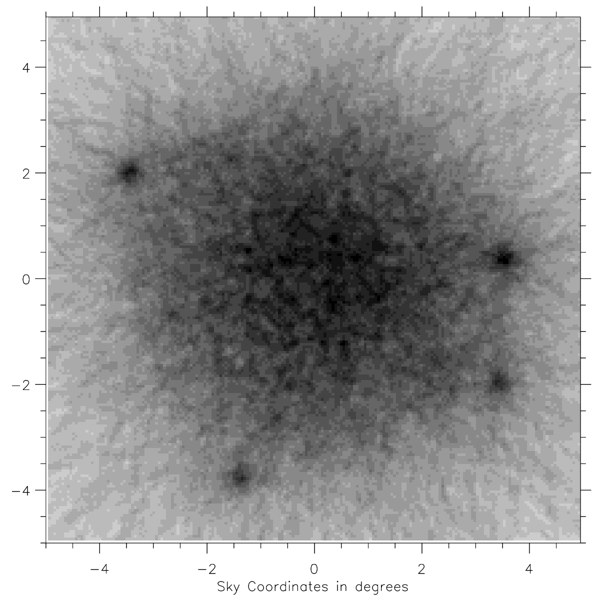

Fig. 7: Simulation of a 10^6 sec ATHENA observation of the Vela supernova remnant in the 1809 keV line of ^{26}Al.. The simulation assumed that the bulk of the aluminum radioactivity is distributed within 2-3 degrees, with a few percent of the radiation concentrated in four explosive fragments. Note that this reconstructed image is an event ring sum that has not been further processed or enhanced.

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[8]Johnson, W. N. et al., 1995, SPIE Proceedings, Vol. 2518, ed. O.H.W. Siegmund & J. V. Vallagra, p. 74