Position Sensitive Germanium Detectors for the Advanced Compton Telescope

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Abstract. The nuclear line region of the gamma ray spectrum remains one of the most challenging and elusive goals of high energy astrophysics. The scientific objectives are well defined, but require well over a factor of 10 increase in sensitivity compared to present day instruments to be achieved. The most promising approach to achieve this sensitivity and a broad range of scientific objectives is offered by an Advanced Compton Telescope (ACT) that would function in the 0.5 to 30 MeV energy range. The ACT builds on the successful COMPTEL instrument on NASA's Gamma Ray Observatory by substituting modern detectors with over an order of magnitude better energy and spatial resolution. Germanium detectors are a natural choice, as they are available in large volumes, provide the best possible energy resolution, and are capable of fine spatial resolution. These improvements alone provide the required gain in sensitivity. Further optimization and the use of more sophisticated techniques promise even greater improvements. We discuss the current status of the germanium detector technology. New results from the characterization of a crossed strip detector using amorphous-germanium contacts and a demonstration of three-dimensional position resolution are presented.

INTRODUCTION

Instruments such as OSSE and COMPTEL on the Compton Gamma Ray Observatory (CGRO) have made many hundreds of observations in the eight years since launch. In all this time, however, many important objectives have yet to be achieved, such as the firm detection of ^{56}Co from Type Ia supernovae. The goal goes beyond simple detection, but to measure the ^{56}Co with an accuracy of better than 10%, thus tightly constraining the models, and the relationship between brightness and width of the light curve. This is important in the application of supernovae as cosmic distance indicators. The upcoming INTEGRAL mission will provide only comparable sensitivity as OSSE and COMPTEL for broad supernova lines. For practical reasons, INTEGRAL and OSSE represents a sensitivity limit for calorimeter types of instruments. Since sensitivity scales roughly as the square root of size and therefore cost, a different detection technology is therefore required.

COMPTEL on the Compton Gamma Ray Observatory (CGRO) represents the first space-based Compton telescope. It has produced impressive results, such as mapping the ^{26}Al distribution in the galaxy. The performance of a Compton telescope depends critically on the energy and spatial resolution of its detectors. COMPTEL uses a liquid scintillator to scatter incoming gamma rays and a NaI scintillator to absorb the scattered energy. This combination permits an instrumental angular resolution on the order of 2-4 degrees rms, and an energy resolution on the order of 5-8% FWHM. Dramatic improvement in both of these measurements are possible using state-of-the art germanium detectors. Our baseline concept for the High-Resolution Compton Telescope (HRCT) will achieve ~1 degree angular resolution and 0.3% FWHM energy resolution at 1 MeV. This should provide a factor of at least 20-30 improvement over COMPTEL for broad line (30 keV) point sources such as Type Ia supernovae, using similar geometry.

The key advance that makes HRCT possible is a new generation of imaging radiation detectors with 10^4 to 10^6 channels of low noise spectroscopy electronics. Germanium detectors are a natural choice, as they: (1) are available in large volumes (up to ~700 cm^3 for a coaxial detector); (2) provide the best possible energy resolution among the semiconducting, gas, and liquid detectors (as good as 1.3 keV FWHM at 1 MeV, and 410 eV FWHM at 100 keV without any electronics contribution); and (3) are capable of fine spatial resolution (<1 mm).

SCIENTIFIC CAPABILITIES

The HRCT will address a broad range of scientific topics [1]. One of the chief objectives of the HRCT is to study line emission from nucleosynthetic radioactivity from supernovae and novae. The HRCT sensitivity should permit the detection of ^{56}Co (847, 1238 keV) to distances ~30 Mpc. The HRCT should then measure the total mass of ^{56}Co to a precision better than 10% in several supernovae per year, thus discriminating between Type Ia models and validating brightness estimates in the application as a cosmological "standard candle." In a zenith pointed mode, HRCT will provide a survey of >70% of the sky on an orbital time scale. Thus, the high sensitivity and sky coverage should provide both an effective monitor for weak transient phenomena and a discovery potential not possible with narrow field-of-view instruments.

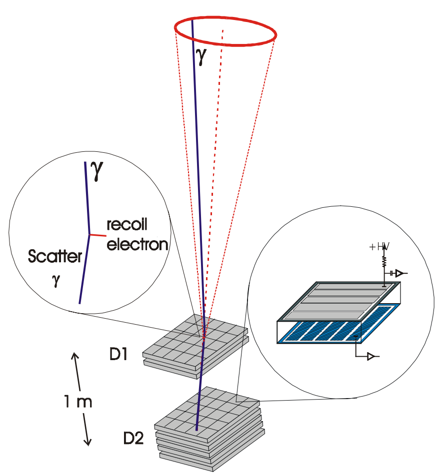

FIGURE 1. Classic Compton telescope in traditional D1/D2 configuration.

PRINCIPLE OF OPERATION

The classic Compton telescope (Figure 1) such as COMPTEL depends on those gamma rays that Compton scatter once in an upper detector, then go on to be totally absorbed in a lower detector. The restricted geometry of a "good event" and the demand for total absorption result in a relatively low efficiency compared with simple calorimeters. This is easily offset by the improved background rejection possible in a Compton instrument. The origin of each individual gamma-ray event is constrained by the measurement to have originated from a cone as shown in Figure 1. The superposition of many such cones forms an image. A detailed discussion of the germanium high-resolution Compton telescope is presented elsewhere [2].

Most good events undergo multiple interactions before they are totally absorbed in D2. It is very important in a high resolution Compton telescope to correctly identify the first two interactions (*i.e.* a single interaction in D1 and the first interaction in D2). These two positions are used to determine the direction of the scattered gamma ray, and thus the axis of the cone shown in Figure 1. This is achieved by accurately measuring the position and energy of each interaction, then sorting out their order based on simple consistency and probability tests [3].

There are several competing concepts for next generation Compton telescopes, generically called the Advanced Compton Telescope (ACT). Some of the primary candidates include highly segmented semiconductor detectors such as germanium, silicon, and CdZnTe detectors. High-pressure gas detectors also have potential advantages, particularly in making large, fully-active volumes. Good spatial and energy resolution are essential in unraveling the interaction sequence and reconstructing the energy of the incoming gamma ray in all of these concepts.

The generalized ACT concept can make full use of events that interact 3 or more times in any order within the detectors, even if the total energy is not totally absorbed by the active detector volumes [4]. The distinction between detectors D1 and D2 is no longer important. Utilization of partially absorbed events dramatically increases the telescope efficiency, but requires sophisticated detectors. The energy of the incident gamma ray, E_i, is fully determined from the first three interactions by,

$$E_i = \Delta E_1 + \frac{\Delta E_2 + \sqrt{\Delta E_2^2 + 4\Delta E_2 m_e c^2 / (1-\cos\theta_2)}}{2}, \qquad (1)$$

where ΔE_1 and ΔE_2 are the energy losses of the first two interactions, and θ_2 is the scatter angle of the second interaction, determined by measuring the positions of the first three interactions. It is not necessary to fully absorb the energy of the gamma ray in order to measure its energy. Monte Carlo simulations of the ACT concept implemented using only silicon detectors indicate that very high efficiencies are achievable. Roughly 30-40% of 1 MeV photons incident on a detector are usable (37 g-cm^{-2} total active thickness), depending on assumptions about passive material and practical considerations in the design.

We have constructed an efficient algorithm to determine the interaction order of events within ACT. Essentially, all permutations of possible events orders are evaluated. Those orders that are inconsistent with the pattern of energy loss are rejected. We have found that most 1 MeV events with four interactions are uniquely reconstructed in the proper order. Events of three interactions typically have one, two, or three solutions for event order. Future work will apply a test to determine which is the most probable of these possible solutions. The simple algorithm becomes computationally intensive for more than about 6 interactions, where pattern recognition or other techniques will be required to simplify the search.

Further work remains to be done to study the background rejection efficiency of these event-order reconstruction techniques. Using all of the information provided by the detectors has the promise of significantly reducing background, and potentially detecting Type Ia supernovae to >100 Mpc for a 1 m^2 sized instrument.

3-D POSITION OF INTERACTION

Accurate measurement of the 3-dimensional positions of each interaction is essential in order to reconstruct the events properly. We achieved this in germanium strip detectors [5]. The germanium strip detector can be made in a variety of sizes, ranging in thickness from a few mm to about 2 cm, and in area from very small to 8×8 cm (possibly 8×16 soon). The position resolution is determined by the segmentation of the electrodes and timing of the signal development on each face. The segmentation, or strip pitch, can be fabricated as fine as required, approaching a practical limit ~100 to 200 microns pitch [6]. The segmentation measures position in two dimensions in a crossed strip detector where strips on one face of the device are perpendicular to the other. The 2-dimensional position of an interaction is easily determined in a crossed strip detector by identifying the strips on which matching signals are measured.

The depth of interaction is measured by the timing of the induced charge on each face of the detector. The bulk of the induced charge develops when the primary ionization is near the strip that collects it. A time difference between the electron and hole collection is observed when the strip pitch is small compared to the detector size, and is approximately ±100 ns in a 1 cm thick germanium detector. The pulse shape can be computed by considering weighting potentials of the electrodes within the detector, and folding these with the motion of the drifting charge carriers [5].

The depth of interaction is measured rather simply: the time that the preamplifier output rises to 50% of the full signal is recorded. The difference between the times of crossing for the signals on each face is proportional to depth.

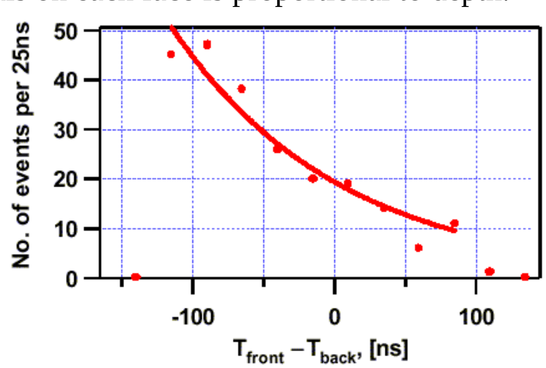

FIGURE 2. Depth of interaction for 122 keV gamma rays in 1 cm thick germanium strip detector.

A test was performed using a 122 keV gamma ray source. The time to rise to 50% full scale was computed from the preamplifier trace for each event. A histogram of the time differences between front and back are plotted in the Figure 2. The full-scale range of time differences corresponds to 10 mm depth in the detector. The exponential fit has a decay length of 5.6 ± 0.6 mm, in good agreement with the 5.75 mm attenuation length of a 122 keV gamma ray in germanium.

AMORPHOUS GERMANIUM CONTACTS

Until recently, the n^+ contacts on germanium strip detectors were fabricated with a lithium diffusion process. While lithium diffused contacts have excellent electrical properties, the diffusion depth is >300 microns, thus limiting the finest pitch that can be reliably produced to >1 mm, and creating a significant dead layer around the contact. An alternative to lithium diffusion has been developed at Lawrence Berkeley National Laboratories using a thin layer of amorphous germanium to form the contact [7]. It is expected that these devices will require less labor and fewer critical steps to produce than the lithium-diffused contact devices that are commercially available today. By removing the diffusion depth restriction, amorphous germanium contacts allow much finer contact structures to be fabricated.

We have tested a crossed strip detector that was produced using this technology [8]. This detector has a negligible surface dead layer, and has been demonstrated to be stable, even after annealing at 100°C for 24 hours (annealing may be required on orbit to recover from prolonged exposure to radiation over a period of years). The device was 1 cm thick with an active area of 1.5×1.5 cm^2, and 5 strips on each face. The strips were spaced on a 3 mm pitch with 0.25mm gaps separating them. The device performed well as expected, with sharp strip boundaries and good energy resolution (<2 keV FWHM limited by the electronics used). We are in the process of fabricating a larger device with 2 mm pitch strips and 5×5 cm^2 active area.

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