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Overview of the nuclear Compton telescope

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Abstract

The nuclear compton telescope (NCT) is a balloon-borne soft γ-ray (0.2–15 MeV) telescope designed to study astrophysical sources of nuclear line emission and γ-ray polarization. NCT utilizes an array of 12 3-D imaging germanium detectors (GeDs). A 2-GeD prototype of NCT is scheduled to be flown in Spring 2004. The NCT program is designed to develop and test the technologies and analysis techniques crucial for the Advanced Compton Telescope, while studying γ-ray radiation with very high spectral resolution, moderate angular resolution, and high sensitivity. NCT has a novel, ultra-compact design optimized for studying nuclear line emission in the critical 0.5–2 MeV range, and polarization in the 0.2–0.5 MeV range. The prototype flight will critically test the novel instrument technologies, analysis techniques, and background rejection procedures we have developed for high resolution Compton telescopes. In this paper we present an overview of the NCT prototype instrument.

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1. Introduction

The nuclear Compton telescope (NCT) is a balloon-borne soft γ-ray (0.2–15 MeV) telescope designed to study astrophysical sources of nuclear line emission and γ-ray polarization (Boggs et al., 2001, 2002). It employs a novel Compton telescope design (Fig. 1), utilizing 12 high spectral resolution germanium detectors (GeDs) with the ability to track the location in three dimensions of each photon interaction. The tracking serves three purposes: imaging the sky using Compton imaging techniques, measuring polarization, and very effectively reducing background (Boggs and Jean, 2000, 2001).

At the heart of NCT is an array of large volume, 3-D positioning cross strip GeDs, which are being developed using LBNL's amorphous Ge contact technology (Luke et al., 1992). Each of the flight GeDs (Fig. 2) is a 37 × 37 cross-strip p-type

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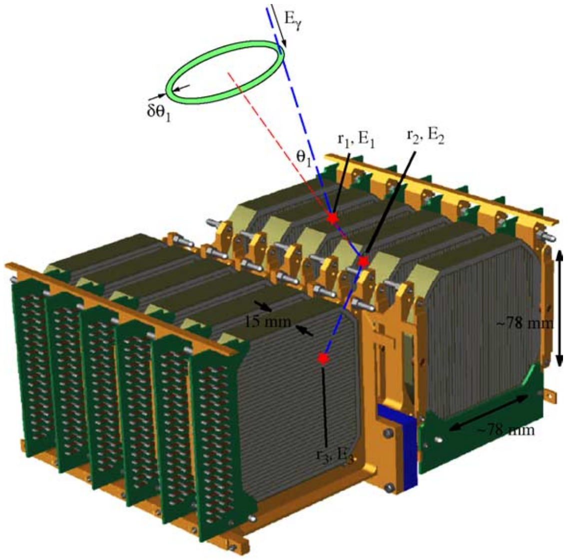

Fig. 1. The heart of NCT is an array of 12 cross-strip GeDs with 3-D position resolution, excellent spectroscopy, sensitivity to γ-ray polarization, and high efficiency.

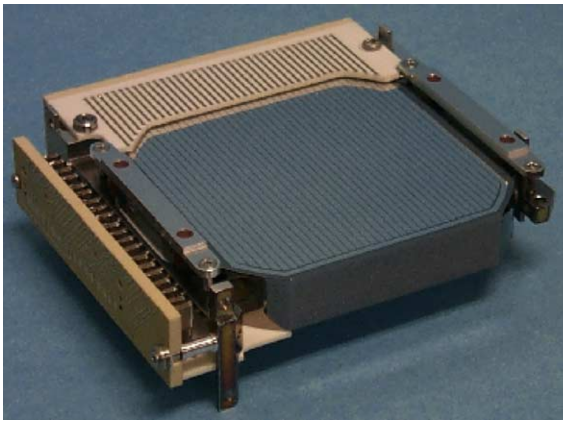

Fig. 2. Photograph of one of our two flight detectors. Each detector has 37×37 strips, and an active volume of 82 cm^3 containing over 41-thousand pixel-volume elements used to track each incident γ-ray as it scatters through the detector.

planar detector, 15-mm thick. The strip pitch is 2 mm, with a 0.2-mm gap chosen to minimize the effects of charge sharing between strips. The strips define an active area of 51 cm^2. A 2-mm wide guard ring surrounds this active area on both faces of the detector, with a 1-mm gap between the ring and the edge of the crystal. The depletion voltages are typically −800 V, and we operate the GeDs at −1000 V. The GeDs are cryogenically cooled by a copper cold finger running to a 50-L liquid nitrogen dewar. The entire set of detectors and their cryostat is enclosed inside an active BGO well (Fig. 4), giving an overall field of view of 3.2 str. The instrument is mounted in a pointed, autonomous balloon platform and is capable of long duration (~2 week) balloon flights.

The primary technological goal of NCT is to explore a new phase space of source-dominated nuclear γ-ray observations. Some of the long term science goals of NCT include mapping both ^{26}Al and ^{60}Fe in the plane and bulge of our galaxy, measuring the amount of ^{44}Ti contained in recent core collapse supernova remnants, measuring with high resolution the spectra of AGN and searching for their γ-ray polarization, looking for polarization in the emission from pulsars and associated plerions, and searching for redshifted deuterium lines from the surfaces of neutron stars.

2. 3-D positioning

There are two main keys to Compton imaging with this system. The first is to accurately determine the energy deposited in the detector at each interaction. The second is successfully tracking, in all three dimensions, the γ-ray interactions within the detector. When a photon interacts in a GeD, either by photoabsorption or Compton Scattering, a fast recoil electron is produced which knocks more electrons from the valence band to the conduction band, leaving holes behind. The number of *e–h* pairs is directly proportional do the energy deposited (1 *e–h* pair per 2.98 eV). In an applied electric field (bias voltage), these *e–h* pairs will separate and drift in opposite directions, electrons toward the anode and holes toward the cathode. By segmenting the anode into strips, and the cathode into orthogonal strips, 2-D positioning is achieved directly through identification of the active anode and cathode strips.

Measuring the "depth", or "*z* position", of the interaction in the detector (the distance between the γ-ray interaction and either the anode or cathode strip), is achieved by measuring the difference between electron and hole collection times on opposite faces of the detector. The Collection Time Difference (CTD) for an event is well defined, and has been shown to be linear with depth to first order (Amman and Luke, 2000; Amrose et al., 2002). The drift time across a 15-mm thick GeD is on the order of 150 ns.

Digitizing the charge signals for the NCT balloon flight instrument is impractical due to the power and size constraints. Instead, we have developed a simple analog constant fraction discriminator which records the time when each channel signal reaches 50% of its maximum amplitude (Coburn et al., 2003). Our analog electronics have achieved an 0.5 mm FWHM resolution at 60 keV – which is comparable to digitizing results, but with a much smaller, simpler, lower power system.

The calibration of the interaction depth in terms of the CTD poses a unique problem since we cannot send in events of known depth. We can, however, use photopeak events of varying energies, which have known depth distributions determined by the mean free path at each energy. This depth calibration is discussed in detail in Amrose et al. (2003) and Coburn et al. (2002).

3. Detector electronics

NCT uses conventional GeD quality signal processing electronics (see Coburn et al., 2003 for overview). Each detector strip has a compact, low power signal processing chain made predominantly of conventional surface mount components. Detector signal extraction is accomplished with a unique charge sensitive preamplifier, in which excellent spectroscopic performance is achieved in a small footprint and at modest cost and low power, without sacrificing signal bandwidth (Fabris et al., 1999). A much-simplified pulse-shaping amplifier, with both a fast and slow channel, follows each preamplifier. The slow channel, with a 8 μs peaking time, is followed by a peak detect and stretch function. The fast channel uses a small delay line constant fraction discriminator to time stamp each waveform at 50% of its maximum amplitude, generating a low time walk signal. Demonstrated resolutions are 1.2 keV FWHM spectral resolution at 60 keV, and 0.5 mm FWHM depth determination for all interactions that deposit $\geqslant 20$ keV. Spectroscopy signals uniquely match the fast-signal pairs for multiple interactions in the same GeD.

One 16-channel signal-processing cluster resides on a single printed circuit card ("cluster board"), with both the fast and slow analog signal processing electronics. Five cluster boards are required for each GeD. The cluster boards connect into a common back plane, which supplies bi-directional housekeeping communication, power, and event data channels. Low level input signals connect to the front panel well away from the back plane. Each cluster board has two ACTEL Field Programmable Gate Arrays (FPGA), one which keeps track of the LLD, ULD and fast trigger rates in each strip, and the second which coordinates the logic between the slow and fast channels, as well as the shield veto signals. A single DSP for each detector interfaces between the 5 identical ACTEL sets, one set for each cluster board, and the main flight computer. The total power per channel is 210 mW, for a total consumption of 197 W for the full 12-GeD instrument.

4. Spectral performance

Since our GeDs are cut from a single, homogeneous germanium crystal, their efficiency, spectral resolution, and position resolution are uniform across the face of the detector (Coburn et al., 2002). Variations between strips are generally on the few percent level, and easily calibrated. Maintaining this uniformity with our flight electronics, as opposed to benchtop electronics, is a high priority in our electronics development and testing. The success of our science objectives requires all 16 channels (8 anode, or DC, and 8 cathode, or AC) on each of the 5 cluster boards for each detector provide similar response. With guard rings, this is a total of 152 channels for the 2-GeD prototype flight, and 912 channels for the full NCT system.

In Fig. 3 we show the results of illuminating a prototype detector with a ^{57}Co source. The data came through the entire flight system, with packetized data read by a GSE computer rather than the main gondola flight computer. With a set of 8 anode and 8 cathode cross strip events, spectra for each of 64 cross strip "pixels" were generated. (Here, we show a 4 × 4 subset for clarity.) The ^{57}Co source was ~1 m from the detector, giving a nearly uniform illumination of each detector strip. Only anode events were used in binning each spectra. Cathode events, which provide redundant spectral information, were only used to identify which AC strip to associate the photon with. The spectral resolutions of each of the anode channels taken with the flight electronics are quite good. On average, the the resolutions obtained with the flight board are identical to what we get using benchtop electronics.

The pixel spectra in Fig. 3 are very uniform. The integrated counts under each 122 keV photopeak vary by less than ±2.7% from the average; similarly, the spectral resolutions for each pixel vary by less than ±12% from the average. There is little evidence for charge sharing, which would appear as tailing below the photopeak energy. As expected, we do not see any significant tailing in the spectra (Coburn et al., 2002).

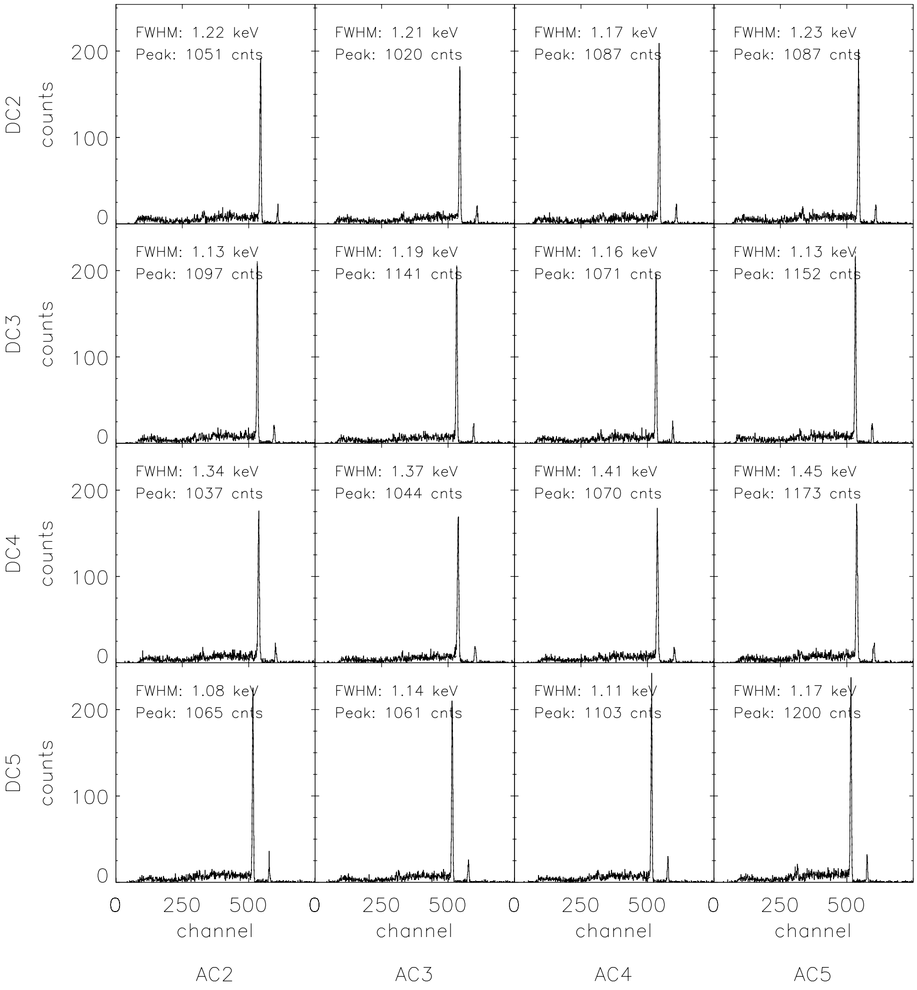

Fig. 3. A complete set of anode spectra for each cross strip pair (pixel) using one cluster board, with 8 anode (DC channel) and 8 cathode (AC channel) electronics channels. (Only a 4 × 4 subset is shown for clarity.)

Fig. 4. NCT flight cryostat during integration tests with the BGO shields into the instrument cradle. The entire cradle assembly pivots to allow pointing at different elevations.

5. Prototype flight

We are currently finishing the fabrication of the two 37 × 37 strip flight detectors. We have finished testing the first of the flight electronics cluster boards, and are currently testing the entire set of 10. The two DSP boards, each of which coordinates the outputs of the 5 cluster boards for a given GeD and passes packetized data to the main gondola flight computer, have been successfully tested. Once we have a full working 2-GeD system, with detectors and a full set of flight electronics, we will begin a series of tests and calibrations to fully characterize and optimize the overall detector performance.

The balloon platform itself, which borrows heavily on HIREGS long duration balloon flight (LDBF) heritage, is nearly ready for flight. In Fig. 4, we show a photograph of the integration of the flight cryostat into the shield assembly. The shield pieces and electronics have been tested since the last HIREGS balloon flight, and the entire system is working as expected. Only minor modifications to the flight computer hardware and software need to be made to integrate it into the new detector system. The GSE hardware is in place, and the GSE software currently under development. We plan on flying this NCT prototype on a conventional continental US balloon flight from Fort Sumner, New Mexico, in the Spring of 2004.

Acknowledgements

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