PROCEEDINGS OF SCIENCE

Overview of the Nuclear Compton Telescope

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The Nuclear Compton Telescope (NCT) is a balloon-borne soft gamma-ray (0.2-10 MeV) telescope designed to study astrophysical sources of nuclear line emission and polarization. It consists of twelve high spectral resolution 3D Germanium strip detectors that track gamma-ray Compton scatter interactions with a resolution better than 2 mm^3. Tracking technologies together with NCT's ultra-compact design provide dramatic improvements in Compton efficiency and sensitivity, achieving a similar effective area to COMPTEL with less than 1% of the detector volume. NCT will be breaking new ground in the measurement of polarized gamma-ray emission from astrophysical sources, while simultaneously providing a testing platform for novel event analysis, background reduction, and imaging techniques. Thus NCT is also serving as technology demonstration testbed for modern Compton telescopes, such as the Advanced Compton Telescope, or a focal plane detector of a gamma-ray focusing telescope. The instrument is currently being prepared for a 36-hour flight from New Mexico in Spring of 2009, followed by a long duration flight from Australia. On these science flights, NCT will map the Galactic positron annihilation, ^{26}Al, and ^{60}Fe emission, and perform a discovery study of polarization from all classes of gamma-ray sources. We present an overview of the NCT instrument, the planned flight program, and preliminary results of calibration and performance tests.

7th INTEGRAL Workshop
September 8-11 2008
Copenhagen, Denmark

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PoS(Integral08)152

1. Introduction

The NCT telescope consists of an array of twelve 3D Ge γ-ray detectors (GeDs) that operate on the principle of Compton imaging illustrated in Fig. 1A. At least three Compton interactions per photon allow the ordering of the interactions to be reconstructed and the direction of the incoming photon to be determined to within an annulus in the sky [1]. Compton tracking serves three purposes: imaging the sky, measuring polarization, and reducing background [2]. This compact design also allows to achieve large effective areas and high sensitivity to polarization when compared to predecessor Compton telescopes such as COMPTEL [3].

The detectors are surrounded on the bottom and sides by an active BGO shield, and have an overall field of view of 3.2 str that can be further reduced by a set of collimator slabs (Fig. 2, collimator slabs not shown). The instrument is carried in an autonomous, pointed balloon gondola (Fig. 3). NCT's detector array is optimized for sensitivity in the nuclear line regime of 0.5-2 MeV, with an energy resolution of 2.5 keV FWHM at 1 MeV.

A two GeD prototype of NCT successfully flew on a technology demonstration flight in 2005 from New Mexico [4],[5]. The current flight program consists of two balloon flights with a ten detector array. The first is a conventional (24-48h) flight from New Mexico in 2009, followed by a Long Duration Balloon Flight (LDBF, ~20 days) from Australia in 2010. Details of these flights are described in section 5.

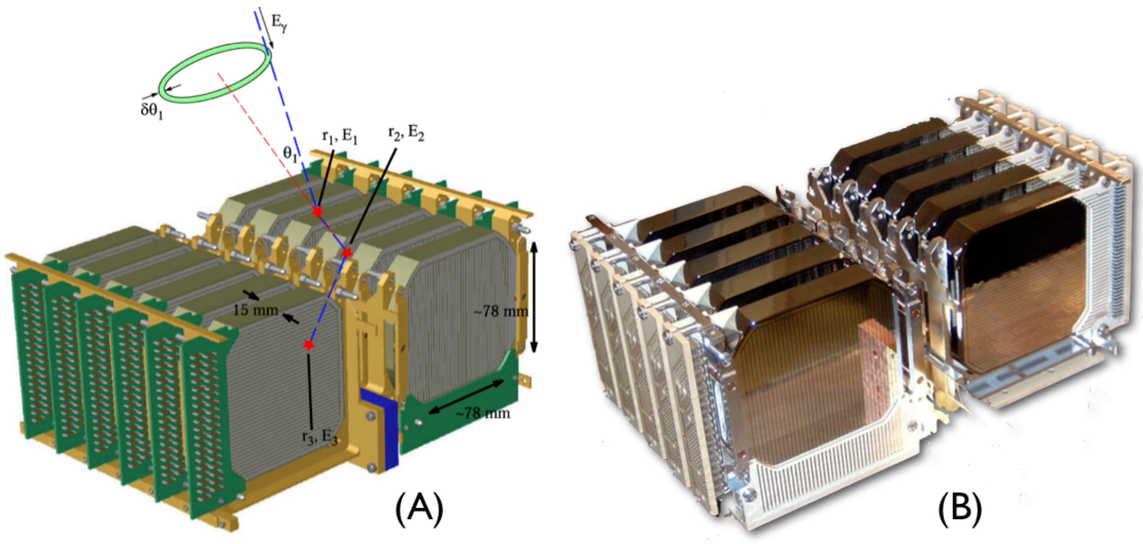

Figure 1: The heart of NCT is an array of twelve cross-strip GeDs with 3D position resolution, excellent spectroscopy, sensitivity to γ-ray polarization, and high efficiency. (A) Twelve GeD detector CAD model showing principle of Compton Imaging. (B) Photograph of ten integrated GeDs for the upcoming flight in Spring of 2009.

2. Instrument

a) 3D GeDs

The detectors for NCT consist of 15 mm thick cross strip GeDs of active area 5400 mm^2 each, fabricated at the Lawrence Berkeley National Laboratory (LBNL). 37×37 orthogonal 2 mm pitch electrode strips on opposite faces provide 2-D positioning. Charge collection time determines the depth of the interaction, which allows for a full 3D position resolution to 1.6 mm^3. A gap of 0.25 mm between the strips for the 2.0 mm pitch has been demonstrated by LBNL to minimize the number of charge sharing events and the resulting charge loss, while maintaining the high GeD spectral resolution [6]. Each detector is surrounded by a guard ring which is instrumented to provide veto signals.

Due to impurity problems with two of the raw Ge crystals obtained from the manufacturer, only ten of the twelve detectors fabricated are suited for science measurements. These ten GeDs have been mounted on a central coldfinger and integrated into the NCT cryostat (flight detector array shown in Fig. 1B).

NCT's detectors have been described in more detail in [5], [6], and [8].

b) Cryogenics

The NCT GeDs are housed in a single cryostat that successfully flew on the 2005 prototype flight (see Figs. 2 and 3). The cryostat is attached to a single 50 liter liquid nitrogen dewar which cools the GeDs to 85 K for over 20 days. The dewar is vented through a 5 psi valve keeping the liquid nitrogen under pressure at float.

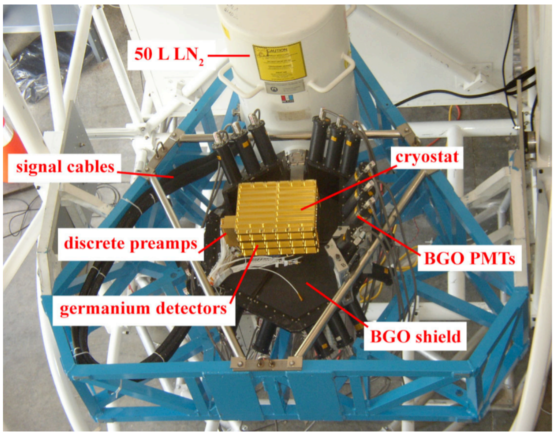

Figure 2: . The cryostat as it is situated in the balloon gondola. Note the white LN_2 dewar behind the cryostat and the active BGO shielding surrounding the sides and bottom of the cryostat. An active CsI collimator can be added, constraining the field of view even further.

c) Shields

The cryostat is enclosed on the sides and bottom by a 5 cm thick active bismuth germanate (BGO) anticoincidence scintillator that significantly reduces instrumental background. Shield rates at float (3.1 g/cm^2) were ~12,000 counts/s during the prototype flight, and were largely responsible for the instrument dead time of 8%. A more precise determination of the required shield veto signal window will possibly reduce the dead time in upcoming flights. If further collimation is desired, a set of four 5 cm thick CsI slabs (not shown in Figures) can be installed to reduce the field of view to ~1 str.

d) Electronics

NCT uses conventional GeD quality signal processing electronics [8]. The signal for each detector strip is extracted by a low-power, charge-sensitive preamplifier [9] achieving 25 mW/channel. A pulse shaping amplifier, with both fast and slow channels, follows each preamplifier. The slow channel, with a 6 μs time-to-peak unipolar shaper, is followed by a peak detect and stretch function. The fast channel uses a bipolar shaper to time stamp each waveform at the signal zero-crossing. These systems have been designed for compatibility with future implementation in an ASIC.

e) Gondola

NCT is mounted on an autonomous Long Duration Balloon Flight (LDBF) platform designed for full-sky elevation and azimuthal pointing (Fig. 3 shows the 2005 configuration of the NCT gondola). The cryostat and shields are held in a cradle, which is protected by roll bars. Readout electronics, flight computer, and batteries are enclosed in the electronics bay located at the aft of the gondola. Solar panels have since been added to the gondola to recharge the batteries during daytime in the upcoming flights.

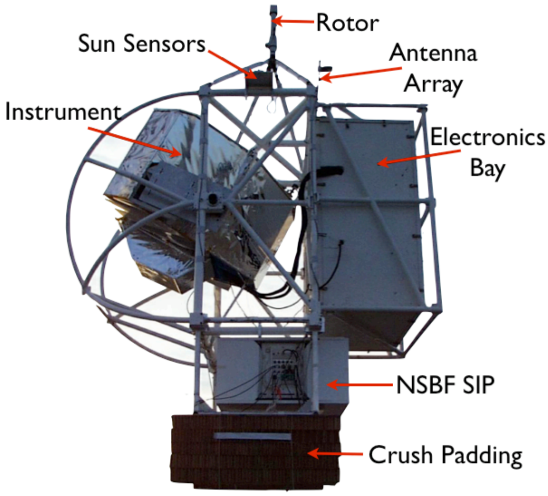

Figure 3: Photograph of prototype flight gondola in Fort Sumner, NM, June 2005. The NCT payload hangs on the flight line with its full LDBF flight systems (except solar power).

The instrument's wide field of view of 3.2 str (without collimator) and moderate angular resolution of $2-3^\circ$ HPHW result in modest pointing requirements of 2° pointing accuracy, with aspect reconstruction to 0.5° or better. A three-axis magnetometer together with a differential GPS receiver, redundantly provide the information required to point the gondola as desired. A rotor assembly allows pointing in azimuth, whereas elevation pointing can be achieved by rotating the instrument cradle. However, our current flight plans do not require changes of pointing in elevation.

f) Data storage and handling

An onboard flight computer (single-board, 1.4 GHz, running Linux) controls the operation of the detectors, readout electronics, and pointing. Scientific and housekeeping data is stored redundantly on two onboard solid state drives at a rate of ~250 MB/detector/day. The National Scientific Balloon Facility Support Instrument Package (NSBF SIP), attached to the gondola, provides data telemetry and remote commanding at a rates up to 384 kbps.

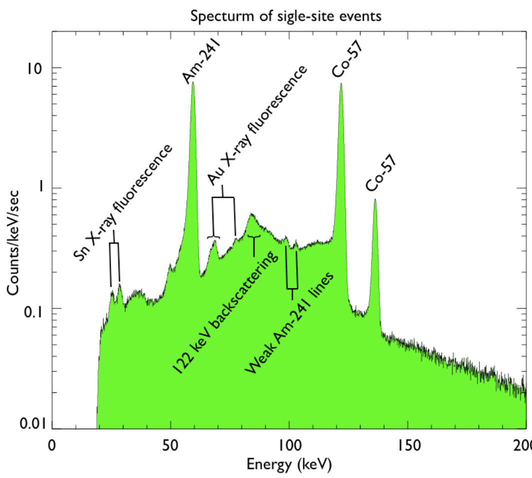

Figure 4: Energy spectrum obtained form one detector using single-site events only (one strip triggered on each side of the detector). This spectrum was taken using an ^{241}Am source (59.5 keV line) and a ^{57}Co source (122 keV and 136 keV lines). Weaker source lines, as well as fluorescence and backscattering lines are also visible. The 59.5 keV and 122 keV lines have a FWHM of 2.00 keV and 2.06 keV respectively.

3. Testing and calibration

The readout electronics for all ten GeDs has been assembled and the ongoing flight preparations are now focussing on detector calibrations of energy, depth, angular resolution, effective area, plus imaging and polarimetric capability. Preliminary laboratory results for one detector (shown in Figs. 4 and 5) confirm the instrument's expected spectral capabilities.

4. Selected science goals

a) Positron Astrophysics

The production mechanism of positrons and their annihilation in the Galactic interstellar medium is still topic of debate after three decades of observations. NCT will map the Galactic central radian 511 keV distribution with S/N ratio of $\sim 36\sigma$ with 2.5° resolution. Although SPI achieved significantly better S/N (50σ in the first year [10]), NCT's wide FoV provides uniform Galactic center exposure and a better intrinsic capability for mapping large-scale diffuse emission, giving NCT some advantages over SPI for these studies.

b) Core-Collapse SNe

^{26}Al has a half-life of 7.2×10^5 yr emitting a characteristic 1.809 MeV photon. The integrated 1.809 MeV flux is widely believed to map core-collapse SNe activity in our Galaxy over the last 10^6 years, corresponding to $\sim 10^4$ combined SNe [11]. Other potential sources for ^{26}Al include Wolf-Rayet (WR) stars, asymptotic giant branch stars, and classical novae [12]. In order to determine the origin of the ^{26}Al, one can trace the abundance of ^{60}Fe, which should be $\sim$40% as abundant as ^{26}Al when produced in core-collapse SNe [13], while the abundance of ^{60}Fe is negligible for ^{26}Al

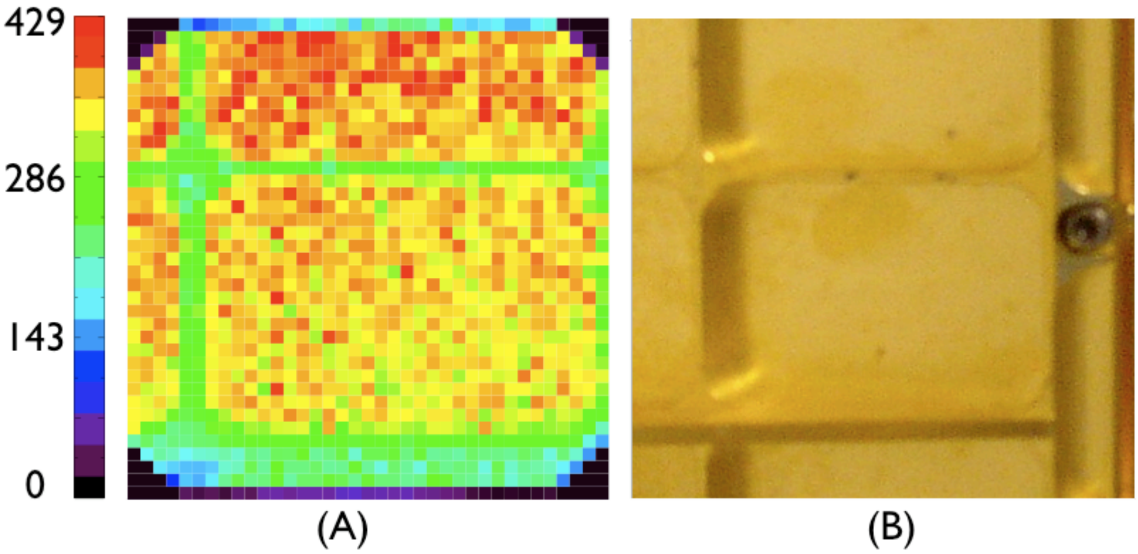

Figure 5: (A) Pixel display of single site events for one detector being illuminated face on by a ^{57}Co source. Notice that the observed non-uniformity arises from rib structures on the exterior of the cryostat. (B) Photograph showing the ribbing of the cryostat. The empty corner pixels in (A) are due to the octagonal shape of the GeDs (see Fig. 1)

produced in WR stars. The ^{60}Fe to ^{26}Al flux ratio near the galactic plane has been independently measured to be 0.16 by RHESSI [14] and 0.11±0.03 by SPI [15], confirming predicted ratio of 0.16 for SN explosions [13]. NCT will map the ^{26}Al distribution, spatially resolving the 1.809 MeV line position and width along the Galactic plane, and also measure ^{60}Fe abundance with a goal of a 5σ detection, improving on the $\sim 3\sigma$ measuremens by RHESSI [14] and SPI [15].

c) Physics in the Supernova Core

^{44}Ti, which decays to ^{44}Ca via ^{44}Sc, can serve to probe the physics of core-collapse SNe explosions [16], as it is produced near the region that falls back to form a compact object. Its half-life of 58.9±0.3 years [17] makes it a good tracer for young SNe in the Milky Way. Current estimates of the Galactic core collapse SNe rate is 1.9±1.1 per century [18], implying ∼8 young supernova remnants (SNR) should be visible in their ^{44}Ti emission. COMPTEL discovered only one source in the ^{44}Sc decay line at 1.157 MeV (Cas A) and saw some controversial evidence for a second SNR in Vela [19], [20]. INTEGRAL's instruments have reaffirmed the Cas A detection [21], but no additional ^{44}Ti sources have been detected to date. NCT should be able to confirm these sources and, with its 700 km/s FWHM, be able to provide meaningful constraints on the true expansion speeds and radial ^{44}Ti distribution. It will also search for new sources of 1.157 MeV emission, including the young Kepler SNR.

d) Polarization Measurements

Our goals for polarization measurements are to constrain the polarization of the Crab nebula in the upcoming flight. We anticipate an independent verification of the recent SPI polarization measurement [22] using our instrument, which has been optimized to track Compton interactions. If we observe a bright GRB during the long duration balloon flight (∼80% probability for fully polarized GRBs), we should also be able to measure its polarization.

5. Flight program

a) Prototype flight (2005)

A prototype instrument consisting of two GeDs was successfully launched from Fort Sumner, New Mexico on June 1, 2005. The mean altitude at float was 40 km (atmospheric overburden of 3.1 g/cm^2) and the instrument acquired data for 5.5 hours before termination. The primary goals for this flight were to qualify the gondola for long duration balloon flight and measure the instrumental background, telemetry rates, data vault needs, etc., at float. These objectives were achieved as the instrument and associated electronics performed flawlessly [23].

A failure in the azimuthal pointing system limited the exposure of the instrument to

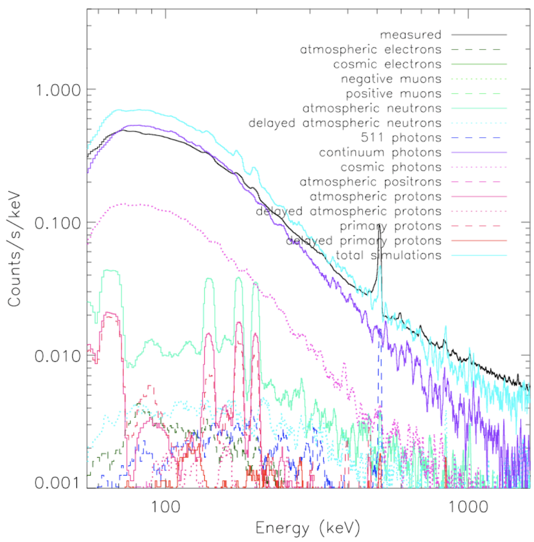

Figure 6: The measured background at float (in black) is compared to the simulated background components and their sum (in cyan) for the June 2005 flight. The measured background agrees with our simulations to within 4.5% for energies above 300 keV [24].

the primary sources and significantly complicated the science analysis. However, the prototype flight enabled a thorough characterization of the background spectrum. Fig. 6 compares the background spectrum of this flight to its simulated components.

b) Upcoming flights in New Mexico (2009) and Australia (2010)

Two upcoming flights are planned for NCT with different scientific objectives.

The first flight, planned to launch in Spring 2009 from Fort Sumner, New Mexico, will be a conventional turnaround balloon flight (24-48 hours) somewhat longer than the test flight. For this flight the detector will consist of ten GeDs (see Fig. 1B) and will focus on observing γ-ray point sources visible from the northern hemisphere, such as the Crab pulsar and Cygnus X-1.

The second flight planned will be a long duration balloon flight from Alice Springs, Australia in December 2010. The goal is to circumnavigate the earth in $\sim$20 days at 40 km altitude. This flight will focus on observing and mapping diffuse Galactic γ-ray emission, such as the 511 keV positron annihilation line. The southern latitude will enable observations of large regions of the Galactic plane over an extended period of time.

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