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Calibration of 3D positioning in a Ge cross-strip detector

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Abstract

In preparation for the Nuclear Compton Telescope, a novel gamma-ray telescope designed for balloon-borne astrophysical observations, we have calibrated, the 3D positioning capabilities of a prototype 2 mm pitch cross-strip Ge detector. To accurately position in the third dimension (depth) we use the relative timing difference in charge collection on the anode and cathode, a sensitive measure of depth in the detector. In order to calibrate the depth determination in terms of the collection time difference, we have developed a statistical calibration technique which involves illuminating opposite sides of the detector with photons of known energy and requiring self-consistency of the measured mean free path of the photons on both sides. Requiring this to occur simultaneously for several different photon energies ensures that there will be no energy dependence of the calibration (within our sensitivity range). We can then check for consistency with the known mean free paths in germanium for each photon energy, as well as with our detailed simulations of the detector performance. We present the result of our prototype detector calibration as well as demonstrate the excellent agreement between these calibrations and our simulations.

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Keywords: Germanium detector; Calibration; 3D

1. Introduction

The Nuclear Compton Telescope (NCT) is a balloon-borne soft gamma ray (0.2–1.5 MeV) telescope to study astrophysical sources of nuclear line emission and polarization [1]. At the heart of NCT is an array of large volume, 3-D positioning, cross strip germanium detectors (GeDs) which have been developed and tested using LBNL's amorphous Ge contact technology [2]. The prototype 19 × 19 strip GeD is an 11.0-mm thick, p-type planar detector. Orthogonal strips were deposited on both faces of the GeD, with a strip pitch of 2.00 mm, and a 0.50-mm gap between strips. The strips define an active area of 3.8 × 3.8 cm^2. A 4-mm wide guard ring surrounds this active area on both faces of the detector. The depletion voltage is −1600 V, and we operated the GeD at −2000 V for these tests. We instrumented the strips on both the ground side (DC coupled) and HV side (AC coupled) with custom low power, low noise preamplifiers.

The 2-D positioning is achieved directly through identification of the active anode and cathode strips during an event. The positioning in the third dimension is achieved by measuring the difference

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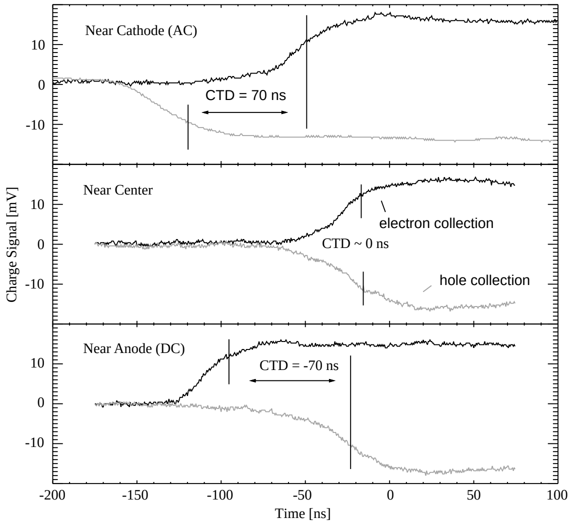

Fig. 1. Induced signals on anode and cathode strips of our prototype GeD, for 122 keV photon events near the anode (top), the GeD center (middle), and the cathode (bottom). Our 3-D electronics use a simple delay line to time-tag each strip signal as it crosses 50% of its maximum amplitude.

between electron and hole collection times on opposite faces of the detector (see Fig. 1). This collection time difference (CTD) for an event is well defined due to the sharp rise in the weighting field near the collecting strips. To the first order, the CTD is linear with depth [3,4].

2. Calibration

The calibration of the interaction depth in terms of the CTD poses a unique problem since we cannot create events of known depth in the detector. We can however send in events with a known depth *distribution*. The mean free path (MFP) of photons in germanium is well known, so for a single energy photon beam we can predict the distribution we should see to high accuracy. If we illuminate opposite faces (AC and DC) of the detector with photons of the same energy, we should see the same distribution in depth on the two sides, and this distribution should be consistent with the known MFP for the photon energy. We can use this as a constraint to find the relationship between depth and CTD. We simply iterate to find the calibration resulting in the expected uniformity between best fit MFPs on both sides of the detector. We also require that the same calibration simultaneously result in uniformity at a second photon energy. To make sure we have the right solution, we verify that the final best fit MFP is consistent with the known MFP appropriate for each energy.

We have measured the CTD distribution from the NCT prototype detector using two collimated sources, ^{241}Am (60 keV) and ^{57}Co (122 keV). We irradiated both the AC (cathode) and DC (anode) sides, obtaining approximately 10,000 waveform pairs per side per source. Each waveform pair included the charge rise with time for both the holes and electrons collected from each photon event. We digitized each waveform with a resolution of 0.4 ns using a digital oscilloscope interface. From each pair, we extracted the time difference (anode minus cathode) between the points at which 50% of the total charge was attained, giving us the CTD. These distributions are shown in Fig. 2.

One can see that these distributions are slightly non-uniform between the AC and DC illuminated sides. We characterize the uniformity between distributions using the ratio of the best fit exponential attenuations for each side, which we refer to as the *uniformity index*. Uniform distributions will have a uniformity index equal to unity. Using the *uncalibrated* CTD distributions in Fig. 2, this index was found to be 0.90 ± 0.05 for 60 keV and 0.79 ± 0.09 for 122 keV. The final calibrated distribution should yield a uniformity index of unity for both energies simultaneously.

3. Charge rise simulations

Using our iterative approach, we need an initial guess at the depth versus CTD relationship. We found this using extensive Monte Carlo simulations coupled with a charge transport model [4]. We used the GEANT package to produce a list of interaction depths and energies for events from collimated 60 and 122 keV sources. We then simulated the electric and weighting field inside the detector to follow the holes and electrons

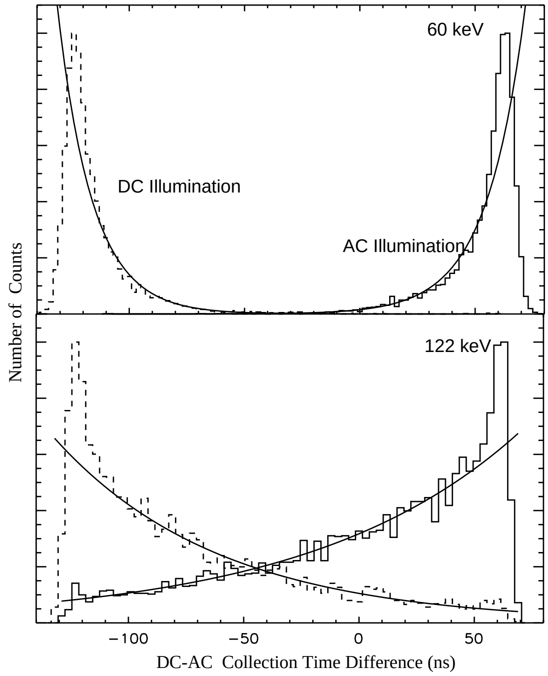

Fig. 2. Distribution of collection time differences (CTD) from the NCT prototype detector for both DC and AC illumination by sources at two photon energies: 60 keV (top) and 122 keV (bottom). Simple exponential attenuation curves are shown for comparison.

across the active volume. For each interaction, we calculated the charge induced with time (in 0.5 ns steps) and found the CTD with the same software pipeline used for the prototype detector data. Using only events with single interaction sites, we found the relationship seen in Fig. 3. It is linear to first order over the bulk of the detector volume. However, to account for the small deviations from linearity, we parameterize the simulated data using a best fit third-order polynomial.

It is apparent from the simulations (Fig. 3) that we can expect slight deviations from linearity for the first and last 0.05 cm (5%) of the active volume. These edge effects are also seen in the prototype data as apparent overpopulations (compared to an exponential attenuation) at high and low CTD (Fig. 2). These effects are due to the sharp rise of the weighting field (which determines the charge signal induced on an electrode) very near a given cathode or anode.

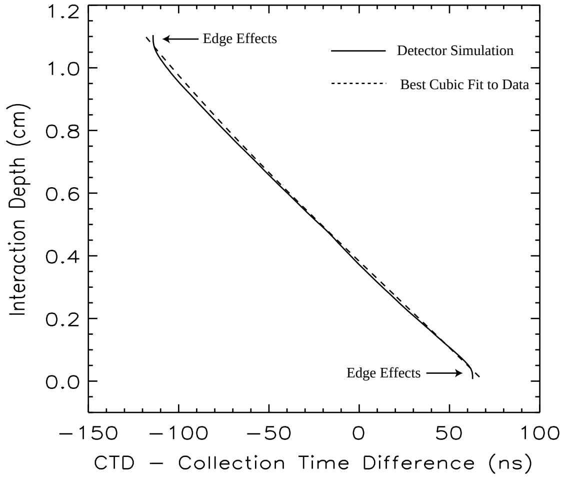

Fig. 3. The interaction depth with CTD found using simulations (solid). The final calibration curve is shown for comparison (dashed).

4. Fitting to the uniformity

In order to determine the depth vs. CTD curve which maximizes uniformity between the AC and DC illuminated data for both the 60 and 122 keV photon distributions, we have defined a statistic S:

$$S = \left(\frac{\Delta\lambda_{60}}{\sigma_{60}}\right)^2 + \left(\frac{\Delta\lambda_{122}}{\sigma_{122}}\right)^2 \tag{1}$$

where $\Delta\lambda$ is the absolute difference in the measured MFP for the AC and DC sides. This measured MFP will depend on our calibrated depth vs. CTD curve, and will be minimized for the curve that optimizes uniformity at both energies. Here we are optimizing a cubic fit to this curve, defined by a 4-element array, a, of the polynomial coefficients. The uniformity between AC and DC sides for 60 and 122 keV was already quite good using our initial curve, a_0, given by the best cubic fit to the simulation data of Fig. 3. The uniformity index values, 0.93 ± 0.05 for 60 keV and 0.90 ± 0.14 for 122 keV, indicate that the simulations are working well. However, to find the values minimizing S and get an independent calibration based only on experimental data, an iteration prescription was applied. Beginning with $a = a_0$, each iteration involved the following: (1) convert the original CTD distributions for 60 and 122 keV using curve a, (2) fit these converted distributions to three-parameter exponentials, and (3) calculate the parameter S. One parameter in curve a was changed for each iteration. The set of parameters minimizing S were kept as the final calibration curve a_f. Given the edge effects seen in both the real data and the simulation, all exponential fits to the converted depth distributions used only the region $0.05 < Z < 1.05$ cm.

The coefficients of the final calibration curve were found to be $a_f = [0.348, -0.00548, 1.52e-06, -2.60e-08]$ and the curve a_f is shown over the simulation result in Fig. 3. The differences between a_f and the original simulation guess a_0 were $<8\%$, again indicating that the simulations are working very well. The final uniformity index was found to be 1.00 ± 0.05 for 60 keV and 1.00 ± 0.17 for 122 keV. The final distributions in interaction depth can be seen in Fig. 4 where the best fit attenuation (using a_f to calibrate) is shown.

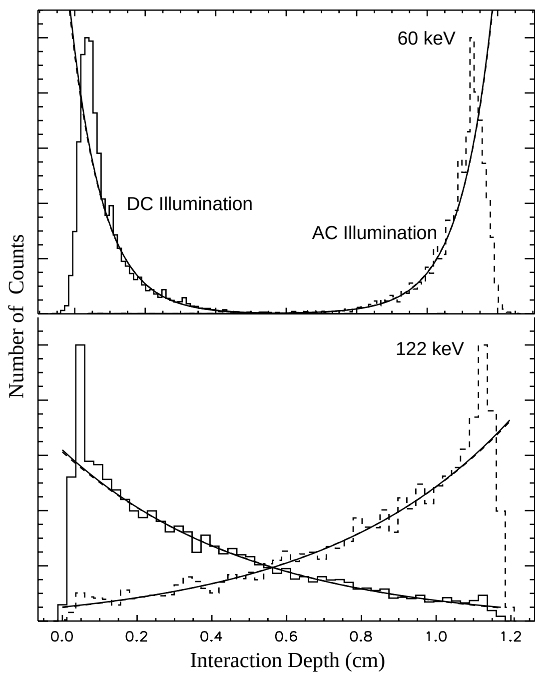

Fig. 4. Final calibrated depth distribution from the NCT prototype detector for both DC and AC illumination at two different photon energies: 60 keV (top) and 122 keV (bottom). The best fit exponential attenuation for each are shown.

5. Checking the result using the MFP

Given the final calibration curve, we can check its accuracy by comparing to the known total MFP for 60 and 122 keV events in germanium. The total MFP is 0.093 cm for 60 keV and 0.518 cm for 122 keV [5]. The measured MFP using the final calibration curve on the prototype detector was 0.093 ± 0.004 cm for 60 keV and 0.495 ± 0.059 cm for 122 keV, consistent with the known values. This agreement indicates that the statistical method does indeed provide a very good calibration between the interaction depth and measured CTD.

6. Conclusions

We have developed a statistical method to calibrate the 3D positioning of the NCT prototype germanium detector. By fitting to the uniformity of the measured mean free path for AC and DC illumination simultaneously for two different photon energies, we have found a single self-consistent calibration. The total MFPs measured using the calibrated data are consistent with the known total MFPs in germanium for the appropriate photon energies, providing an independent check of the accuracy of our calibration. In addition, the independent calibration to experimental data agreed very well with the calibration curve calculated, from detailed simulations. This test provides an independent check of our simulations and suggests that they are accurately modeling charge transport and signal induction in these detectors.

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