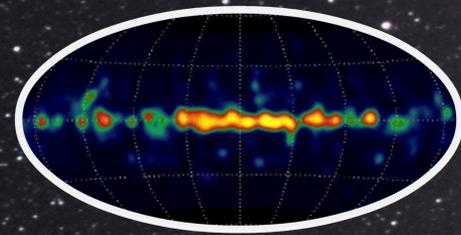




Goals, Development, and Performance of the Compton Spectrometer and Imager's Anti-Coincidence Subsystem

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Summary

The Compton Spectrometer and Imager (COSI) is an upcoming NASA Small Explorer mission focused on exploring the 0.2-5 MeV energy range in the electromagnetic spectrum. This MeV gap has long been underexplored due to technical challenges, in particular the high instrument and astrophysical backgrounds in this energy regime. COSI aims to conduct spectroscopy, imaging, and polarimetry of cosmic gamma-ray sources to study galactic positrons, galactic element formation, accreting black holes, and contribute to multi-messenger astrophysics. COSI utilizes sixteen germanium detectors (GeDs) for high-resolution spectroscopy and an Anti-Coincidence Subsystem (ACS) comprised of twenty-two Bismuth Germanate (BGO) scintillation crystals coupled with Silicon Photomultipliers (SiPMs). The ACS provides active shielding, detects γ -rays escaping the GeDs, monitors background radiation, and triggers transient alerts. Achieving a low energy threshold for the ACS is crucial for anti-coincidence vetoing and detecting transients. For COSI's ACS, SiPMs have been selected over photomultiplier tubes (PMTs) due to their low voltage, weight, and volume. Contrary to other scintillators which prefer a large number of SiPMs to read out the signal, we find that a 3x3 SiPM array centered on the narrow side of a BGO scintillator is enough to provide the best possible energy threshold. In this research, we provide an overview of the COSI ACS detector system, and report on results from various performance tests of the BGO detectors and the flight-like readout system.

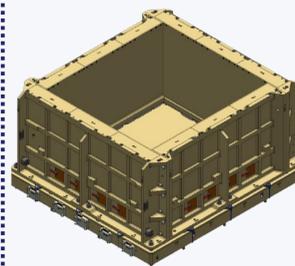
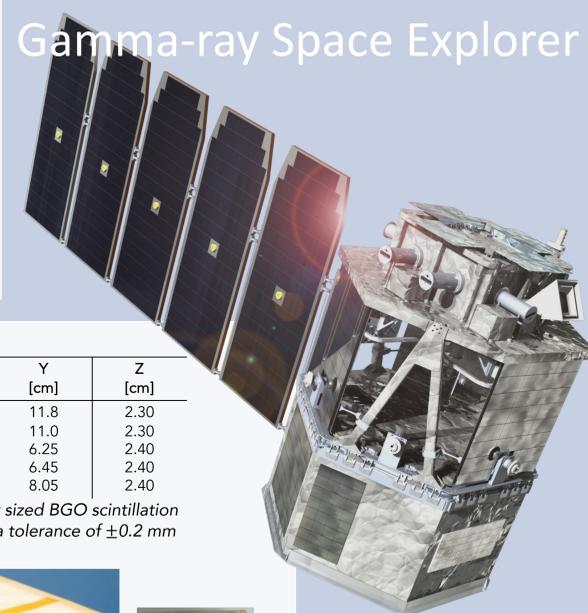


Figure 1: Compton Spectrometer and Imager's Anti-Coincidence Subsystem system.

COSI

Gamma-ray Space Explorer



Introduction

- The Compton Spectrometer and Imager explores the low-energy γ -ray regime, which holds clues to key astrophysical questions, including:
 1. The origin of the 511 keV antimatter annihilation γ -ray line coming from the Galactic Center region as first seen over 50 years ago by [1]; 2. the life cycles of massive stars and their supernovae [2]; 3. polarization in extreme environments such as GRBs, black holes, and AGN [3]; 4. and Multi-messenger astrophysics in the "MeV Gap".
- COSI is composed of sixteen high spectral resolution germanium detectors (GeDs) that provide 3D positions of γ -ray interaction sites along with an Anti-Coincidence Subsystem (ACS) that shields the telescope on five sides.
 - COSI ACS consists of 22 Bismuth Germanate (BGO) scintillation crystals that are read out using Silicon Photomultipliers (SiPMs). The signal from the SiPMs is processed using ASICs (flight) or Multichannel Analyzers (lab electronics). BGO sizes are shown in Tab. 1 and a fully wrapped BGO is shown in Fig. 2.
 - Two energy channels: low-energy, 80 keV to 2 MeV, and high-energy, starting at 2 MeV.
 - While BGO's high density makes it ideal for shielding and background monitoring, its low light yield means that its performance does not degrade with fewer SiPMs. BGO performs best with a 3x3 SiPM array, balancing electronic noise and signal.

BGO Type	X [cm]	Y [cm]	Z [cm]
BGO X-Wall	19.4	11.8	2.30
BGO Y-Wall	19.4	11.0	2.30
BGO Z-Wall 1	19.8	6.25	2.40
BGO Z-Wall 2	17.1	6.45	2.40
BGO Z-Wall 3	19.8	8.05	2.40

Table 1: Dimensions of different sized BGO scintillation crystals. BGO scintillators have a tolerance of ± 0.2 mm in all three dimensions.



Figure 2: Left: A fully wrapped BGO detector used for the EM X-Wall ACS System. Right: 3x3 SiPM array board as used on the EM X-Wall ACS System and the FM ACS System.

For a more complete overview of COSI, see [4].

Results & Discussion

Primary Requirements of ACS: The primary requirement of the ACS is a low energy threshold, essential for vetoing low-energy events in the GeDs at low energies. This low energy threshold aids in the vetoing of beta-decay-originating positrons, resulting in a lower background in the GeDs and in the detection of short GRBs by observing more photon flux (Tab. 2). Energy resolution is less of a concern since the reported energy bins are large.

Energy Threshold [keV]	Photon flux ^b [ph/cm ² /s]	Relative sensitivity @ 511 keV [%] (smaller is better)
50	2.39	99
80	2.06	100
100	1.88	101
150	1.53	104
200	1.27	-
300	0.88	-
∞	-	220

^bintegrated from threshold [keV] to 1 MeV

Table 2: The short GRB photon flux is modeled using a Band function with parameters from [5]: $\alpha = -0.5$, $\beta = -2.3$, and $E_{\text{break}} = 490$ keV. Relative COSI GeD sensitivity for the positron annihilation line (511 keV) is also presented at various energy thresholds of the ACS.

Wrapping of BGO: COSI ACS BGO crystals are wrapped with 2 layers of VM2000 (thin, 65 μm non-metallic specular reflector used by [6] on the Fermi-LAT calorimeter), 1 layer of PTFE Tetratex (white teflon based wrap that forms around the VM2000), and one layer of PTFE Teflon (76 μm). From Fig. 3 we see that molded VM2000 performs better than scored VM2000 with a lower energy threshold and energy resolution that is improved from from 11.7% (scored) to 10.76% (molded) at 662 keV.

Optimal Number of SiPMs: Unlike other scintillators that benefit from full-face SiPM coverage, BGO achieves comparable or better energy thresholds with fewer SiPMs, as shown in Fig. 3, due to its low light output. Hence, a 3x3 SiPM array was chosen for the ACS FM BGO detectors because it consumes less power and yields a low energy threshold.

High-Energy Channel: A crude calibration of COSI's ACS high-energy channel at the UC Davis proton beam test facility with an original beam energy of 64 MeV. The spectra shown in Fig. 4 reflects the performance of the high-energy channel, which is crucial to approximating the radiation damage to GeDs and modeling the high-energy background.

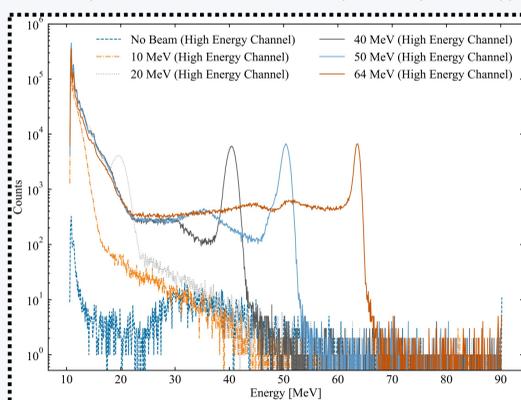


Figure 4: Calibrated energy spectra from the high-energy (proton) channel of one BGO detector in the ACS. Shown is an original 64 MeV proton beam and other attenuated energies, 50 MeV, 40 MeV, 20 MeV, 10 MeV.

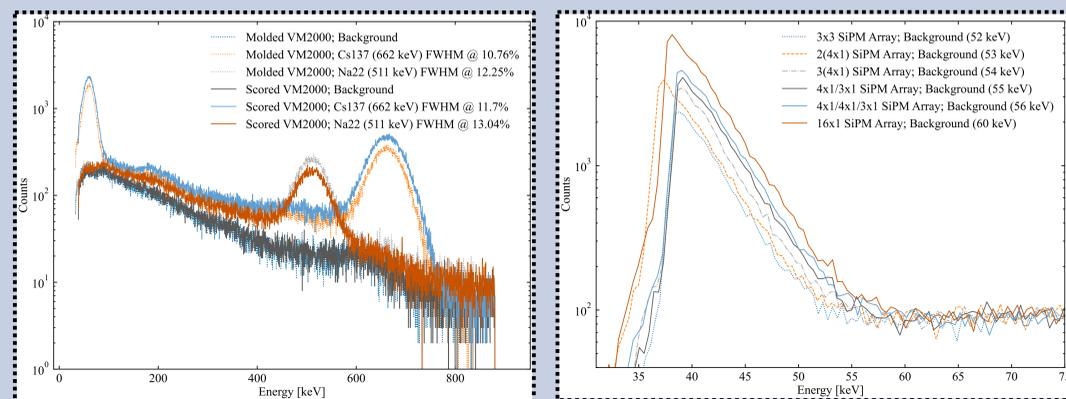


Figure 3: Left: Comparisons of energy resolutions at 511 keV and 662 keV of different wrapping methods. Tested with a 3-1/2" PMT with an 800V Bias. Right: Energy threshold comparison between various SiPM arrays with energy thresholds noted in the legend inside parenthesis. Data calibrated using peaks from ²⁴¹Am (60 keV), ²²Na (511 keV), and ¹³⁷Cs (662 keV).

Conclusions

The Anti-Coincidence Subsystem on COSI is crucial to many science goals and to the reduction of background in the GeD data. With the improvements made through the development process outlined in this paper and poster, we can run the ACS system with a very low energy threshold and obtain good energy resolution. This low energy threshold is critical in vetoing of incomplete events in the GeD and therefore improving the sensitivity of the GeD instrument. The low energy threshold is also crucial for detection of GRBs, which emit predominately at lower energies. The research also helps us save power which leaves a high margin for other high-power consuming parts on the spacecraft.

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