

A compact Germanium spectrometer for nuclear astrophysics

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Emission from electron-positron annihilation at 511 keV was the first extrasolar gamma-ray line ever detected. Despite more than 30 years of theoretical and observational progress, the origin of the positron population has yet to be identified, with potential candidates ranging from microquasars and X-ray binaries to annihilation or decay of dark matter particles. At energies between 200 keV and several MeV, where positron annihilation and most other gamma-ray lines of interest are located, the largest source of instrumental background are secondary protons, neutrons, and photons produced by the spacecraft when it is irradiated by cosmic rays in a space environment. This background is the main factor limiting the sensitivity of current gamma-ray spectrometers, and is proportional to the amount of mass around the detectors. We present progress towards a compact, modular, high-purity Germanium spectrometer that can be integrated into future astrophysics payloads and be the basis of small-satellite missions. A CubeSAT or SmallSAT-class mission based on compact spectrometer modules could have up to 30% of the total spacecraft mass in active germanium crystal, compared to 0.6% in current missions like INTEGRAL, leading to more than an order-of-magnitude improvement in signal-to-noise ratio due the reduction in overall spacecraft mass.

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1. Overview

Studies of the 511 keV positron annihilation gamma-ray line have yet to identify the origin of the population of galactic positrons. The SPI instrument on board *INTEGRAL* has provided the most complete mapping of the 511 keV sky to date. The map reveals an emission morphology unlike that found at other wavelength. A recent SPI-derived model (Fig. 1) shows a bright, extended bulge along with a low surface brightness disk component extending 21° in latitude and a high bulge-to-disk ratio [1]. Neither the shape of the bulge nor the surface brightness are currently well determined. Multiple origins for this signal have been proposed including β^+ emission from the decay of unstable nuclei produced by massive stars or stellar explosions, high-energy particle interactions of cosmic rays with the interstellar medium, compact objects such as millisecond pulsars or microquasars, and the decay of ^{56}Co during Type-I supernovae [2]. More tantalizingly, the broad 21° disk extent has been suggested as a possible signal originating from the annihilation or decay of dark matter particles in the galactic halo. Despite these multiple competing models, no conclusive candidate explanation has emerged.

The limited 16° field of view of *INTEGRAL*-SPI is an inherent limitation to developing a more complete understanding of the nature of the 511 keV sky. A large fraction of the exposure of *INTEGRAL* has been dominated by pointings towards the galactic center and along the inner galactic disk, while exposure at high galactic latitudes remains limited (Fig. 2). An all-sky instrument capable of mapping high galactic latitudes would provide a major step forward in advancing the understanding of current models and potentially lead to new positron sources. The COSI balloon flight in 2016 provided a more uniform coverage of the southern sky but had a sensitivity limited by a 46-day flight duration [3, 4].

An inherent additional challenge in the 511 keV domain is the high instrumental background caused by cosmic ray induced radioactivity in the germanium detector and the surrounding spacecraft material. Figure 3 shows that this instrumental background can be dominant between 200 keV and 2 MeV. Such background is proportional to the surrounding instrument mass [5]. A path to increasing total sensitivity, therefore, is a mission design that maximizes the mass of the germanium spectrometer for gamma-ray collection efficiency while minimizing the passive support structure of the overall instrument to reduce instrumental background. By maximizing the detector's active mass fraction, over an order of magnitude in-

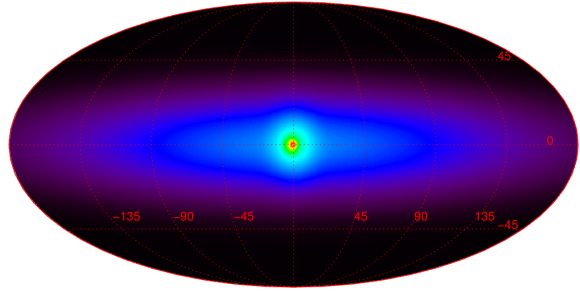


Figure 1: The best-fit spatial components model map of SPI 511 keV data [1].

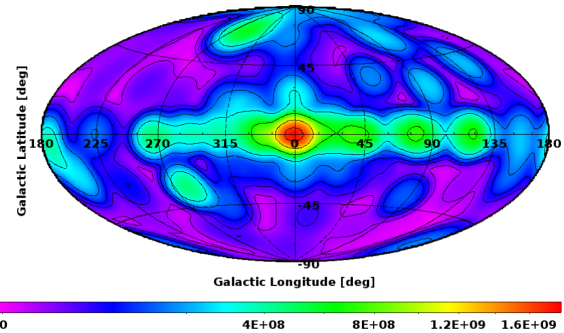


Figure 2: *INTEGRAL* all-sky exposure map, from [1].

crease in sensitivity is possible. A CubeSAT or SmallSAT mission provides a natural basis for such a mission due to industry-induced pressure to design integrated, light-weight, low-power platforms with integrated buses, attitude control, solar panels, and batteries. Using such a platform, a prototype spacecraft can be designed where up to 30% of the total spacecraft mass is active detector. For reference, the germanium detectors in *INTEGRAL* represent only 0.6% of the total spacecraft mass.

2. Prospective detector design

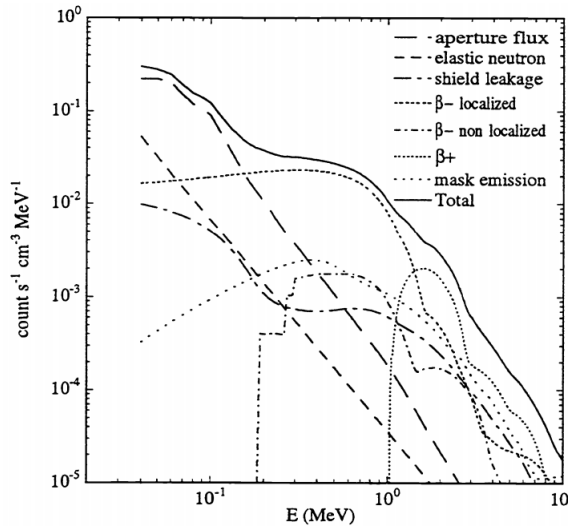


Figure 3: Predicted background to the *INTEGRAL* SPI instrument and its constituent components [5].

measuring changes in the event rate as it orbits its occulting body, either the Earth or the Moon [7]. Such techniques been successfully used on previous experiments, including BATSE [8] and the *Fermi* Gamma-ray Burst Monitor [9]. To reduce the background from direct energy deposition from cosmic-ray events, an anticoincidence shield consisting of a plastic scintillator along with a CsI (or similar) crystal along the back of the detector to reject rear- entering gamma rays. Figure 4 shows a schematic of both a single module and the occultation technique used for source direction determination. A CubeSAT based on this design would could achieve effective areas of $\sim 60 \text{ cm}^2$ at 511 keV (Figure 6), but have comparable sensitivity to *INTEGRAL* ($\sim 90 \text{ cm}^2$) due to its order-of-magnitude lower background; while maintaining a comparable angular resolution and acting as an all-sky instrument.

A potential implementation of a CubeSAT-class mission that optimizes for an active detector mass fraction consist of six $56 \times 53 \text{ mm}$ cylindrical germanium modules in a 12U form-factor. A necessary requirement to achieve the desired 2 keV-at-511 keV energy resolution is operating the germanium detectors at temperatures below 100 K. This can be accomplished with existing space-qualified cryocoolers such as the Space Micro Pulse Tube Cooler by Northrop Grumman [6] while still fitting within the size and power envelopes of a CubeSAT-class mission. Further mass reduction can be accomplished if by implementing an alternative imaging technique than coded masks. One viable alternative is the occultation technique, in which direction reconstruction of the gamma-ray signal is accomplished by mea-

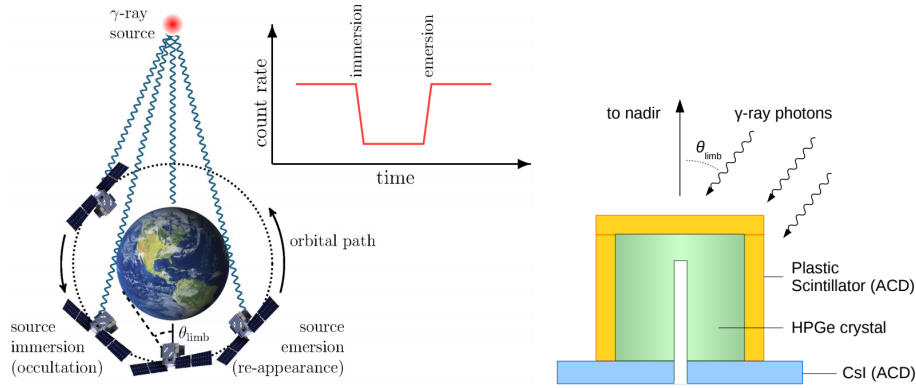


Figure 4: *Left:* Diagram showing the conceptual process of an occultation-imaging spacecraft. *Right:* Cross-section of an individual germanium module that would form the basis of the cubeSAT mission.

3. Simulation

Preliminary simulation of an array of germanium modules and their performances was performed. A hexagonal array of seven 56×53 mm germanium modules was simulated and the detector's effective area at 511 keV was calculated as a function of incident zenith angle. Figure 5 shows the detector layout of this simulation.

The detector simulation was run using the MEGAlib package, a suite of software tools designed to simulate and analyze gamma-ray detectors in the Compton regime [10]. The initial detector geometry was constructed in Geomega and imported into the Geant4-based Cosima program for calculating the detector response to a monoenergetic 511 keV disk emitter and a 2 keV HPGe energy resolution. The simulation output is then analyzed using Revan – real event analyzer – for the reconstruction of the event spectrum and from which the simulated effective area is calculated. Figure 6 and 7 show the effective area as a function of zenith angle and the resulting detector energy spectrum, respectively. The specific detector geometry can be optimized based on the spacecraft's limb angle with the occulting body, which will depend on the orbital altitude of the mission.

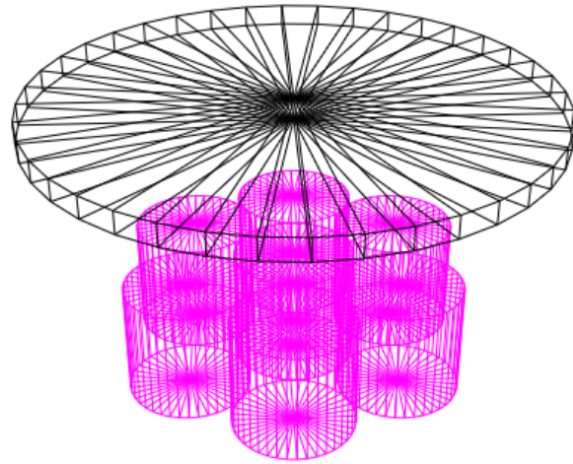


Figure 5: Geomega rendering of the basic HPGe simulation geometry used in the effective area calculations. The black disk indicates the simulated source of gamma rays for calculation of the effective area.

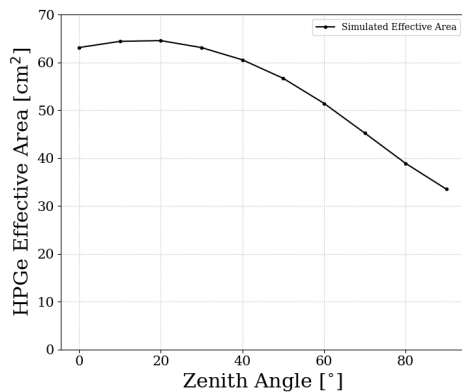


Figure 6: Effective area calculation of the 7-module HPGe at varying zenith angle.

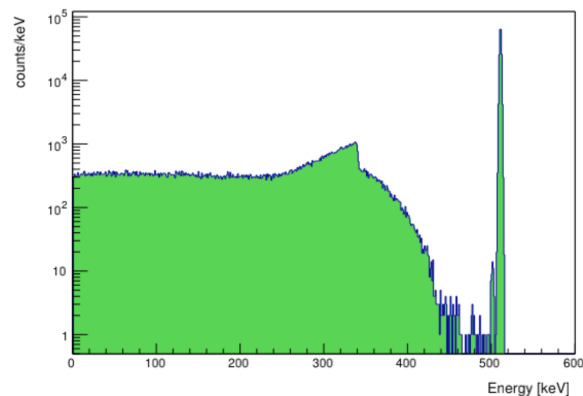


Figure 7: Energy spectrum of the HPGe subject to a 511 keV beam.

4. Summary

The development of a compact, all-sky, high energy resolution instrument utilizing HPGe for gamma-ray spectroscopy is both achievable using currently available technologies and has the potential to provide an order-of-magnitude increase in sensitivity over the comparable *INTEGRAL* spacecraft. The increased sensitivity and all-sky coverage of such an instrument would materially advance our understanding of the kMeV sky, and in doing so provide an important multimessenger probe for cosmic rays, dark matter, stellar nucleosynthesis, and the physics of compact objects. Driven by industry pressure, the quickly maturing CubeSAT and SmallSAT platforms provide the natural basis for such a mission and can provide decreased costs, complexity, and time investment compared to traditional development cycles.

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