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The Small Particle Recognition Kit for Low Energies (SPaRKLE) Onboard Space Rider: A Multi-Purpose Miniaturized Laboratory for Low-Energy Charged Particles and Gamma-Ray Physics

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SPaRKLE (Small Particle Recognition Kit for Low Energies) is a compact detector designed for γ-ray and low-energy charged particle physics in Low Earth Orbit (LEO). The project is carried out by a team of students from the University of Trento and has been selected for the ESA Academy Experiments Programme 2023–2024. SPaRKLE is currently in Phase C (Detailed Definition). Upon successful completion of its development stages, the SPaRKLE payload will be installed on the ESA Space Rider, the first European reusable uncrewed orbiting laboratory, for a mission lasting about two months. During this period, it will measure charged particle fluxes (electrons and protons) and investigate transient phenomena such as Gamma-Ray Bursts (GRBs) and Terrestrial Gamma-ray Flashes (TGFs).

Housed within a CubeSat unit, SPaRKLE features a Cerium-doped Gadolinium Aluminium Gallium Garnet (GAGG) scintillator calorimeter, silicon detectors, and plastic scintillator anti-coincidence detectors. This layout enables event-based particle identification as well as the detection of X-ray and γ-ray photons.

In this contribution, we provide an overview of the project and discuss its scientific, technological, and educational objectives. We also present the performance assessment of the instrument via Geant4 Monte Carlo simulations and show preliminary experimental characterization of the detectors.

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1. Introduction

The study of high-energy astrophysical and atmospheric phenomena from space offers unique scientific and technological opportunities. In this context, SPaRKLE [1] (Small Particle Recognition Kit for Low Energies) is a compact and modular detector conceived for the detection of γ-rays and low-energy charged particles in LEO. The project has been developed within the ESA Academy Experiments Programme 2023–2024 by a student team from the University of Trento.

SPaRKLE is currently in Phase C (Detailed Definition) and is designed to be hosted onboard *Space Rider*, the first European reusable robotic laboratory for in-orbit experiments and sample return. The nominal mission duration is about two months, during which SPaRKLE will operate continuously, measuring the flux of electrons and protons in the inner magnetosphere and investigating transient events such as Gamma-Ray Bursts (GRBs) and Terrestrial Gamma-ray Flashes (TGFs).

Beyond its scientific goals, SPaRKLE also pursues technological and educational objectives. From a technological standpoint, it serves as a pathfinder for miniaturized, low-power detection systems suitable for distributed space architectures. From an educational perspective, it represents a hands-on opportunity for students to engage in real space mission design, testing, and operations under ESA supervision.

This paper outlines the scientific rationale for SPaRKLE, describes the payload design and detection strategy, and presents the results from Monte Carlo simulations and preliminary experimental tests.

2. Scientific Motivations and Mission Objectives

The SPaRKLE mission is designed to address key questions in high-energy astrophysics, atmospheric physics, and space environment monitoring using a compact detector in LEO. Hosted onboard ESA's *Space Rider* platform, SPaRKLE offers a unique opportunity to observe both cosmic and terrestrial radiation phenomena with flexible pointing capabilities.

Among its primary targets are Gamma-Ray Bursts (GRBs), intense flashes of high-energy photons from explosive astrophysical events such as supernovae and neutron star mergers. Understanding their spectral and temporal properties is crucial for constraining emission models and progenitor types. Missions like *Fermi*, *Swift*, and *AGILE* have demonstrated the role of GRBs in multi-messenger astrophysics, as shown by the landmark detection of GRB 170817A [2]. SPaRKLE serves as a demonstrator for compact, low-cost GRB detectors that can contribute to future wide-field alert networks.

On Earth, Terrestrial Gamma-ray Flashes (TGFs) represent brief, intense bursts of gamma rays linked to thunderstorms and lightning activity [3]. Although discovered by chance through GRB detectors, they have become a focus of dedicated missions such as *RHESSI* and *Fermi*. New observations from distributed payloads like SPaRKLE are essential to improve TGF models and broaden spatial coverage.

A third scientific driver is the characterization of low-energy charged particles in LEO, particularly in regions like the South Atlantic Anomaly (SAA) and the polar belts. These particles pose challenges for spacecraft operation and radiation shielding. While traditional models, such

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as AE8/AP8 [4], provide baseline predictions, modern data are needed to capture current space weather conditions. SPaRKLE's low geometric factor allows operation even in high-radiation zones, contributing to both dosimetry and radiation belt studies.

The mission objectives are defined as follows:

- Detect transient γ-ray and X-ray events such as GRBs (deep-space pointing) and TGFs (Earth-pointing).
- Monitor the ionospheric response to space weather phenomena.
- Measure charged particle fluxes in the upper ionosphere, including the SAA and polar regions.

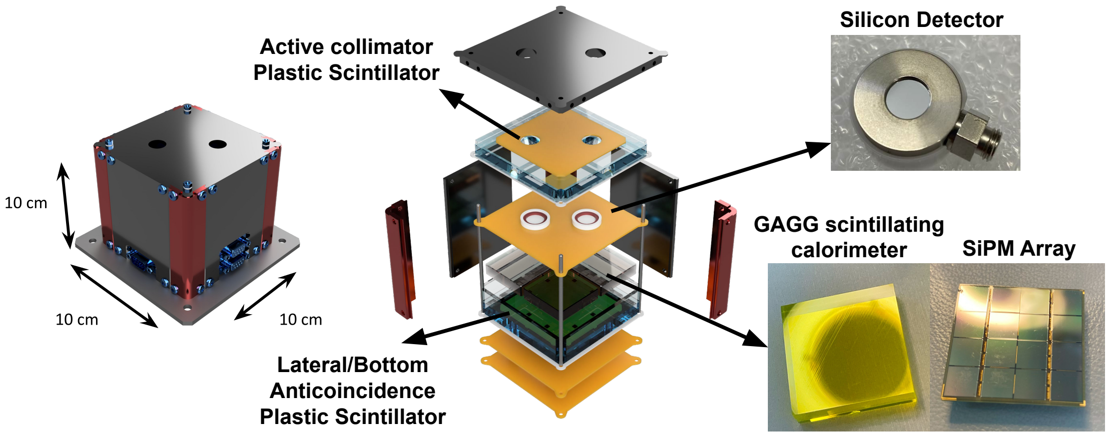

Figure 1: Overview of the SPaRKLE payload. Left: external view of the assembled detector unit. Center: exploded rendering of the payload, showing the stacked sub-components including the silicon detectors, scintillators, mechanical support layers, and outer aluminum housing. Right: photographs of key components under test — top: prototype collimator; bottom left: GAGG:Ce crystal; bottom right: silicon photomultiplier (SiPM) array.

3. Payload Description and Detection Concept

The SPaRKLE payload consists of a layered detection system optimized for compactness and event-based particle identification in LEO. Its geometric configuration is shown in Fig. 1. The core sensing elements include two 100 μm thick silicon detectors and four Cerium-doped GAGG (Gadolinium Aluminium Gallium Garnet) scintillator crystals, arranged to form a stacked calorimetric system. The entire detection volume is surrounded by plastic scintillator panels acting as anti-coincidence shields (ACS), enabling active collimation. All scintillators—both inorganic and plastic—are read out by Silicon Photomultipliers (SiPMs).

This architecture, developed following previous studies on low-energy particle detection [5, 6], enables SPaRKLE to discriminate charged particles via the ΔE–E technique. In this method, the silicon detectors measure the energy lost by a charged particle entering the system (ΔE), while the GAGG crystals stop and absorb the remaining kinetic energy (E). This allows a direct

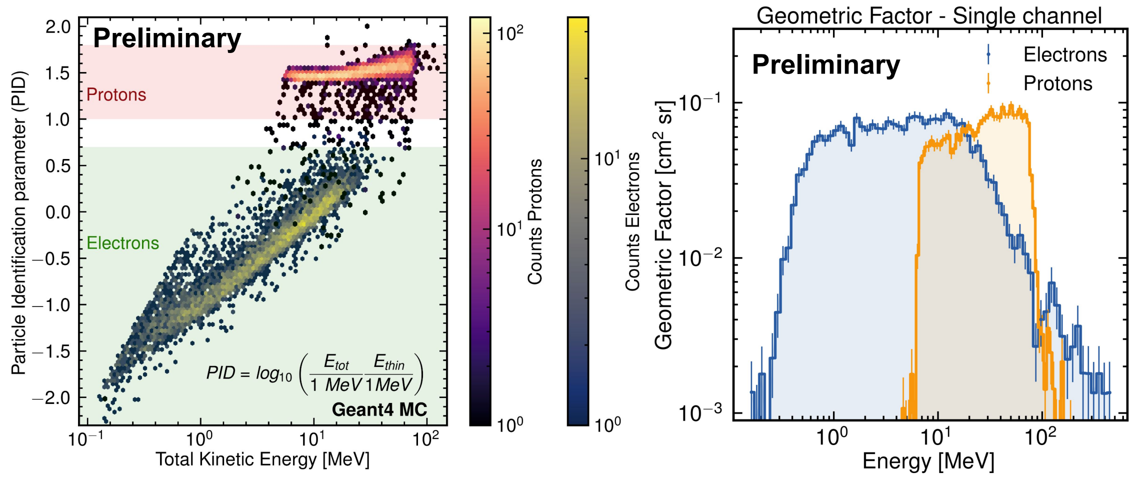

Figure 2: Performance assessment of the SPaRKLE payload based on Geant4 Monte Carlo simulations. **Left**: particle identification (PID) parameter as a function of total kinetic energy for simulated electrons and protons. The parameter is defined as $PID = \log_{10}(\frac{E_{\text{tot}}}{1\text{ MeV}}\frac{E_{\text{thin}}}{1\text{ MeV}})$, where E_{tot} is the total reconstructed energy and E_{thin} is the energy deposited in the silicon layer. Two distinct bands for electrons and protons confirm the $\Delta E{-}E$ identification technique. **Right**: geometric factor as a function of incident energy for electrons (blue) and protons (orange), showing the sensitive energy range of the instrument.

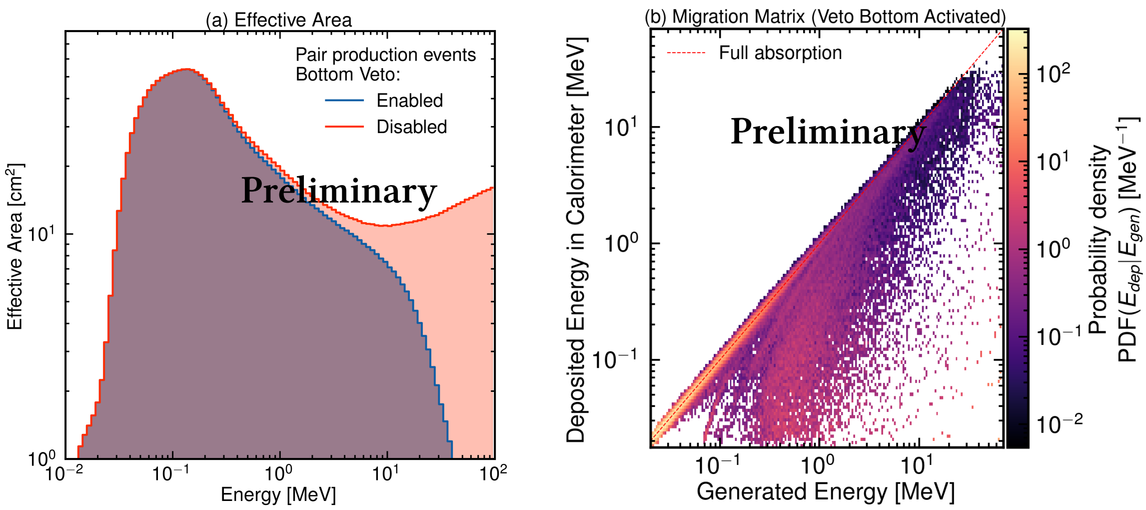

Figure 3: Performance assessment of the SPaRKLE payload for photon detection. **(a)** Effective area as a function of incident photon energy, evaluated with (blue) and without (red) activation of the bottom veto. The veto is used to suppress events with escaping particles from pair production, which become relevant above ~10 MeV. Disabling the veto increases the effective area at high energies but reduces event containment reliability. **(b)** Normalized migration matrix for photon events with the bottom veto enabled. The color scale represents the conditional probability density $\text{PDF}(E_{\text{dep}} \mid E_{\text{gen}})$, i.e., the likelihood of depositing energy E_{dep} in the calorimeter given an initial energy E_{gen}. The dashed red line indicates the ideal full-energy absorption line.

correlation between the particle's stopping power and total energy, facilitating event-based particle identification. Photons (X-rays and γ-rays), on the other hand, deposit their energy in the GAGG calorimeters, typically via photoelectric or Compton interactions, with no signal in the silicon layers.

The detector design includes a plastic veto system on the top side with two channels aligned to the field of view (FOV). This configuration allows for rejection of off-axis particles through topological tagging, ensuring that only particles entering along defined trajectories are accepted.

To quantify the particle identification capabilities, a PID parameter is defined as in Eq. (1),

$$\mathrm{PID}_{\mathrm{parameter}} = \log_{10}\left(\frac{\Delta E}{1\ \mathrm{MeV}}\frac{E_{tot}}{1\ \mathrm{MeV}}\right) \tag{1}$$

combining both the energy deposited in the silicon layer and the total reconstructed energy. This parameter scales approximately with the logarithm of the product mZ^2 for non-relativistic particles and enables a mass- and charge-sensitive discrimination. To see this, note that for charged particles, in the non-relativistic regime the Bethe–Bloch formula [7] implies that the energy deposited in the first silicon layer scales as

$$\Delta E \propto \frac{Z^2}{v^2} \tag{2}$$

Where Z is the charge of the particle and v is its speed. If the event is fully contained—i.e., the particle stops in the GAGG scintillator—and there is no signal in the veto, the initial kinetic energy can be approximated as

$$E_{tot} = E + \Delta E \simeq \frac{1}{2}mv^2 \tag{3}$$

Since the PID parameter in Eq. (1) depends on the product ΔE and E, we obtain $\Delta E \times E_{tot} \propto mZ^2$, and therefore $\mathrm{PID}_{\mathrm{parameter}} \propto \log_{10}(mZ^2)$.

The effective detection capabilities of the SPaRKLE payload have been evaluated through detailed Monte Carlo simulations based on the GEANT4 toolkit [8]. As shown in Fig. 2, the PID distribution reveals two well-separated bands corresponding to electrons and protons, confirming the system's capability to resolve light charged particles over a broad energy range. These results validate the detection strategy and demonstrate the potential of SPaRKLE to provide clean and efficient particle identification in space-based environments.

As shown in Fig. 3(a), the effective area for photon detection was computed under two different selection criteria: with and without activation of the bottom veto. At photon energies above $\sim$10 MeV, pair production becomes the dominant interaction mechanism within the GAGG scintillators. In such cases, secondary particles (typically electrons or positrons) may escape the sensitive volume, leading to partial energy deposition. To retain only well-contained events suitable for spectroscopy, a conservative selection requires no signal in the bottom plastic scintillator (Veto Bottom). This condition ensures full containment but leads to a drop in effective area at high energy, as shown by the blue curve. Conversely, the red curve includes all events regardless of bottom veto activation, thus increasing statistics but losing the ability to reconstruct the photon energy accurately. These events may still be exploited for timing analyses, such as transient detection based on light curve reconstruction, where precise energy resolution is not required.

The normalized migration matrix in Fig. 3(b) further illustrates the detector's spectroscopic performance under the containment condition. The probability density $\mathrm{PDF}(E_{\mathrm{dep}} \mid E_{\mathrm{gen}})$ reflects the expected energy response of the system as a function of the incident photon energy, with the full absorption regime clearly visible along the diagonal.

Overall, the expected detection ranges of the instrument are:

- Electrons: 200 keV to 30 MeV
- Protons: 5 MeV to 100 MeV
- Gamma rays: 20 keV to 10 MeV (for fully contained events)

These results confirm the suitability of the SPaRKLE payload for combined particle and photon detection in the low-to-intermediate energy regime relevant to both astrophysical and atmospheric phenomena.

4. Preliminary Characterization of the GAGG Crystals

The calorimetric system of SPaRKLE is based on Cerium-doped GAGG (Gadolinium Aluminium Gallium Garnet) scintillator crystals, selected for their high light yield, radiation hardness, and fast response. Preliminary laboratory tests were carried out to evaluate the energy resolution, linearity, and light collection efficiency of the system.

For these tests, a single GAGG:Ce crystal with dimensions $40 \times 40 \times 10$ mm^3 was coupled to a silicon photomultiplier tile (SiPM array) developed by FBK. The tile comprises 16 individual SiPMs, each with an active area of 6×6 mm^2, arranged in a compact grid of total size 26.5×27.8 mm^2. Due to the mismatch between the scintillator surface and the photosensitive area of the array, a non-uniform light collection would occur without proper optical coupling, leading to strong position dependence of the signal amplitude.

To mitigate this effect during preliminary tests, a transparent Plexiglass light guide was placed between the crystal and the SiPM array. Although the use of a light guide inherently reduces the number of collected scintillation photons, it homogenizes the optical response across the crystal surface, improving signal uniformity. Optical coupling was performed using EJ-550 optical grease from Eljen Technology, and the scintillator was wrapped with Enhanced Specular Reflector (ESR) film by 3M to maximize light reflection and photon collection.

Fig. 4 summarizes the results of this characterization campaign. Despite the partial photon losses introduced by the light guide, the system demonstrates excellent linearity across the tested energy range and achieves an energy resolution better than 10% for photon energies above 100 keV. These results validate the intrinsic performance of the scintillator material and readout chain. In the final detector design, the light guide will be removed and the SiPMs will be arranged to uniformly cover the entire surface of the crystal, which is expected to further improve both resolution and light yield.

5. Conclusions

SPaRKLE is a compact, multi-purpose detector designed for operation in Low Earth Orbit onboard ESA's *Space Rider*. Its layered architecture and event-based detection strategy enable the identification of low-energy charged particles and high-energy photons with good resolution and

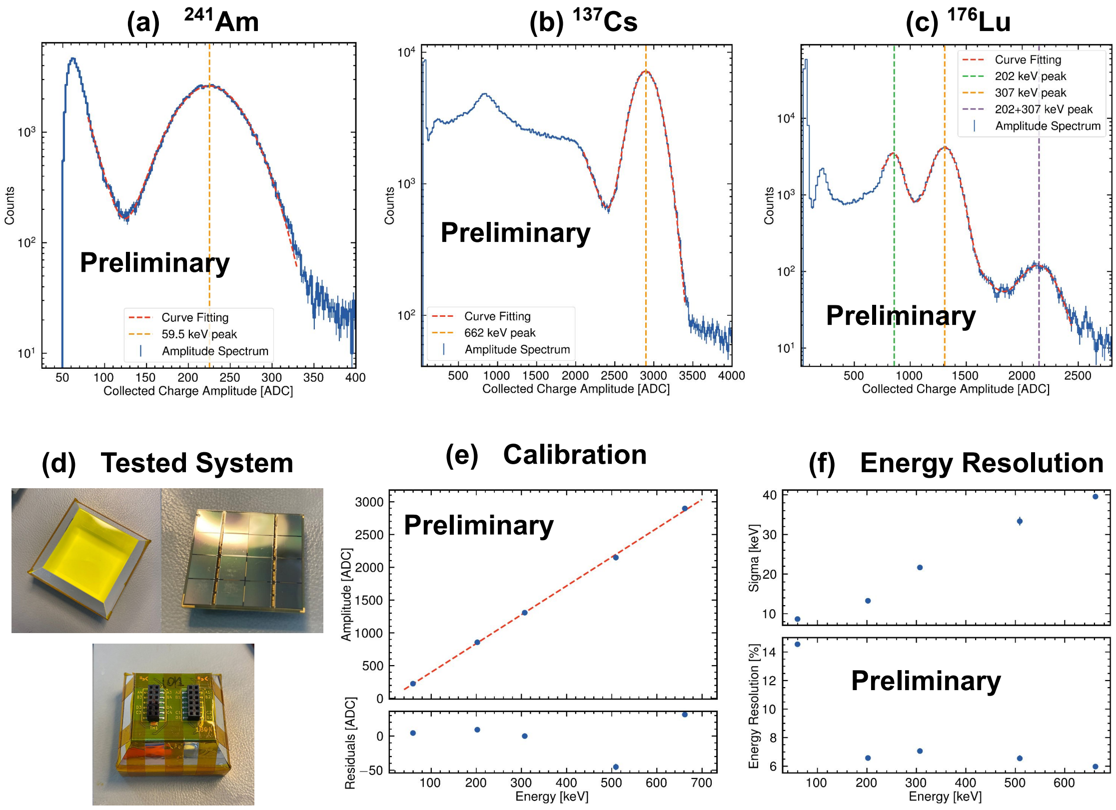

Figure 4: Preliminary experimental characterization of the SPaRKLE calorimeter system using GAGG:Ce scintillators read out by SiPMs. **(a)**–**(c)**: Amplitude spectra obtained with radioactive sources: **(a)** ^{241}Am (59.5 keV), **(b)** ^{137}Cs (662 keV), and **(c)** ^{133}Ba (202, 307, and 509 keV), showing peak identification and Gaussian fits. **(d)**: Pictures of the tested components, including a GAGG:Ce crystal, SiPM array, and custom readout board. A Plexiglass light guide was used to improve light collection uniformity and reduce the position dependence of the scintillation signal. This approach was adopted specifically for this preliminary calibration campaign, as the available SiPM array (manufactured by FBK) had a photosensitive area smaller than the scintillator cross-section. **(e)**: Energy-to-ADC calibration curve with residuals, demonstrating linear system response. **(f)**: Energy resolution as a function of energy, showing both absolute sigma (top) and percentage resolution (bottom). The measured resolution is better than 10% for photon energies above 100 keV.

flexibility. Preliminary experimental tests and GEANT4-based simulations confirm the expected performance and validate the detection concept. The mission will contribute to both fundamental physics and space environment monitoring, while serving as a pathfinder for miniaturized instruments in future distributed space missions.

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