The Crystal Eye instrument and the WINK pathfinder

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Summary. — The Crystal Eye detector is an all-sky spaceborne gamma-ray monitor intended to cover the energy range between 10 keV and 30 MeV, a region currently lacking of extensive observations and monitoring. To optimize its design and estimate its scientific potential, it is essential to understand the environment where it will operate and how it could affect the observation process. With this aim, we assumed the orbital parameters of a potential future mission to be ∼550 km, where the main backgrounds include cosmic diffuse and albedo gamma radiation, primary and secondary protons and neutrons. In this study, detailed GEANT4 Monte Carlo simulations are performed in order to reproduce the response of the Crystal Eye detector in this particle and radiation background environment. The effective area and efficiency are calculated by simulating low energy gamma-ray sources, and used to estimate the detector sensitivity to transient and steady sources. A method to estimate the online transient localization performance of the detector is also developed and discussed. The simulations and results reported here can help optimize the design of the detector, and can be particularly useful as technical references for similar experiments.

1. – Introduction

In the multimessenger astronomy era, there is a high demand for instruments that can monitor wide fields and detect astrophysical transient phenomena with precision. This is especially important in the keV and low MeV regions, where many interesting astrophysical events occur that are not yet well-studied. The Crystal Eye (CE) detector is designed to explore the electromagnetic spectrum from 10 keV to 30 MeV.

The CE detector uses advanced photon detection technologies, such as silicon photomultipliers (SiPM) and new scintillating materials [1]. Its main scientific targets include Gamma Ray Bursts (GRBs), electromagnetic counterparts of gravitational waves, accreting systems, supernovae, and specific gamma emission lines. To observe these phenomena, the detector needs high performance and must handle a complex radiation and particle background. This background includes cosmic diffuse and albedo gamma rays, along with primary and secondary protons and neutrons.

The best performance will be achieved with two hemispherical modules, providing an all-sky view and uniform efficiency. In this study, the GEANT4 [2] simulation toolkit is used to create a detailed model of a single Crystal Eye module and simulate how particles and photons interact with it. This helps estimate the detector's response to its background and calculate important performance parameters like effective area, sensitivity to different sources, and localization ability.

This paper is organized as follows: Section 2 describes the detector and its components. Section 3 discusses the prototype of detector, called WINK.

2. – The Crystal Eye concept

The Crystal Eye design features a hemispherical structure with a 14.5 cm radius, consisting of 112 pixels and weighing approximately 50 kg. It uses two types of crystals, referred to as "up" and "down" crystals, differing in size and mass to ensure a reliable energy range. This compact design is suitable for installation on free-flyer satellites or space stations. We are evaluating two options for the active material of pixels: LYSO (Lutetium Yttrium Oxyorthosilicate) and GAGG (Gadolinium Aluminum Gallium Garnet). The pixels will be read by SiPMs arranged between the layers.

LYSO is a scintillator material based on lutetium (Lu). A notable characteristic of Lu-176, a naturally occurring isotope of lutetium, is its remarkably long half-life of approximately 37.6 billion years, making it stable over geological timescales. Primarily, Lu-176 undergoes beta decay to an excited state of Hafnium-176 (Hf-176). This excited state decays to the ground state of Hf-176 through the emission of gamma rays with energies of 88, 202, and 307 keV. Various combinations of these energies, depending on absorption, will result in different peaks. The sum of 307 keV, 202 keV, and 88 keV gives us the highest energy peak if all these gamma rays are absorbed. Two of them give us peaks at 509 keV, 395 keV, and 290 keV. Additionally, we have single peaks when the remaining two gamma rays escape our active detector.

The alternative is to use GAGG. GAGG is a scintillator material used in medical imaging, security screening, and high-energy physics due to its high light yield and fast response time. It is considered a strong alternative to LYSO, offering better durability and performance for radiation detection and imaging.

Both materials share similar characteristics suitable for our application, and the choice will depend on detailed performance and practical considerations.

Atop the UP crystal is an anticoincidence or veto layer (BC408 plastic scintillator) for photon tagging and charged cosmic-ray rejection. Additionally, there is a continuous anticoincidence layer inside, beneath the DOWN pixels.

In the past, constructing such a design was not feasible due to the size and weight of photodetectors (primarily photomultipliers) and the resulting high costs [3]. However, advancements in new sensors and materials now make this highly efficient, low-cost, compact device possible. Over the last decade, SiPM technology has seen significant improvements, enabling its use in space environments and opening new scientific opportunities.

The shape of Crystal Eye, with hexagonal pyramids oriented in different directions (see the top panel of Fig. 1), provides a 2π field of view (FOV) [4]. Its design ensures:

- **symmetry:** the positioning of the crystals have been studied in order to achieve a uniform coverage of the whole hemisphere, so that all the directions in the FOV will be equally monitored.

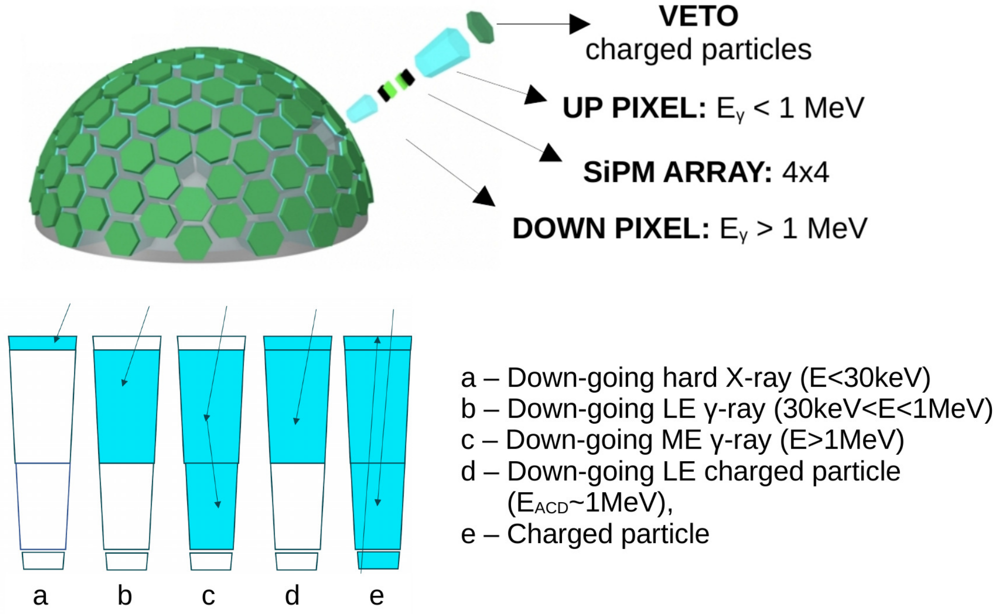

Fig. 1. – Top: Exploded model of the baseline configuration of the Crystal Eye detector. In cyan, the UP and DOWN LYSO pixels. In green, the anticoincidence layer, which will be optimized to improve the hermeticity. Bottom: The trigger concept. In cyan, the triggered elements. E_{ACD} is the energy deposited in the external veto layer.

- **thermal protection:** the SiPMs are shielded from the external environment by the LYSO crystals ensuring the thermal stabilization in the SiPM housing layer.

- **radiation hardness:** the SiPM housing layer is shielded by 4 cm of LYSO on the top and 3 cm of LYSO on the bottom, strongly reducing the radiation damage of the sensors. Preliminary tests show that the dose received by a naked SiPM in 5 years is equivalent to those received in 20 years by a SiPM shielded with 3 cm of LYSO.

The photon identification depends on the event topology, as shown in the bottom panel of Fig. 1. This panel illustrates that a double layer structure and the anticoincidence module are essential for particle identification and therefore a reliable photon trigger. Some possible trigger configurations are illustrated in Fig. 1, where configurations (a), (b), and (c) are considered effective photon triggers.

GEANT-4 based simulations demonstrate that Crystal Eye has large effective area and superior localization capabilities compared to current all-sky monitors [8]. At 1 MeV, the effective area of Crystal Eye is about five times higher than that of Fermi-GBM, as shown in Fig. 2. The effective area results are for the LYSO and LYSO (Up pixels) + GAGG (Down pixels) combination. While the lower limit (30 keV) of the detector's operational energy range is mainly determined by the threshold of the electronic components, the upper limit is influenced by several factors. The effective area curve shows a decreasing effective area beyond 50 MeV. Additionally, simulation calculations of energy

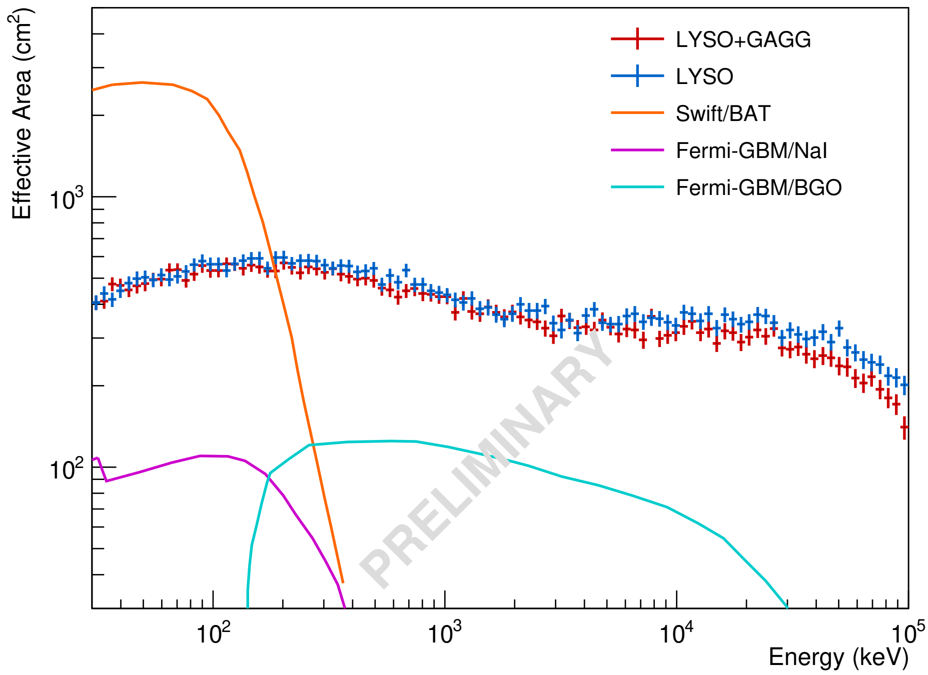

Fig. 2. – Crystal Eye effective area compared with the one of Swift [5] and Fermi-GBM [6].

containment in the detector crystal material reveal that photons up to 10–20 MeV deposit nearly all their energy in the detector, except for those with shorter path lengths interacting near the dome's periphery. However, photons around 100 MeV, which are not fully contained within our detector, on average lose about 20 percent of their initial energy. Furthermore, there is a limitation imposed by the dynamic range of the electronic

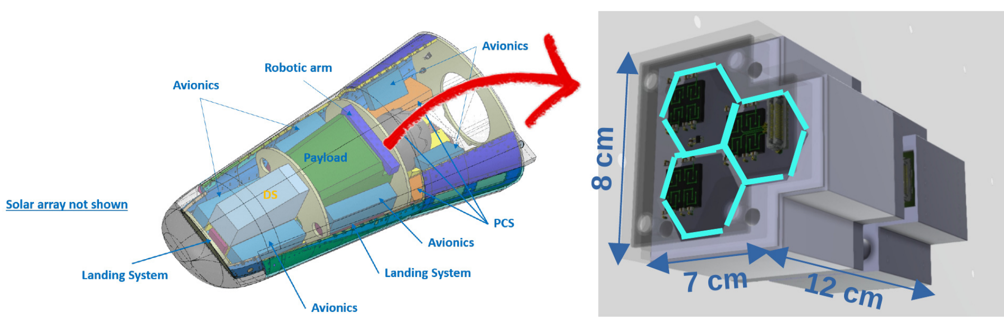

Fig. 3. – Left: The Space Rider vehicle by ESA which will host WINK in its MPCB (green) whose dimension are 1x1x1 meters. WINK will be installed on a thermal plate (purple) to ensure power dissipation. Right: A CAD model of WINK, where the three pixel are highlighted.

readout system to prevent signal saturation. These constraints suggest a conservative and preliminary upper limit of the operating energy at approximately 50 MeV.

3. – WINK

A Crystal Eye prototype named WINK is being developed for a pathfinder mission on the ESA Space Rider vehicle. This uncrewed robotic laboratory, equipped with pointing capabilities, is scheduled for its maiden flight in 2025. After its launch on Vega-C, Space Rider will remain in low Earth orbit for about two months before returning to Earth with its payloads. It will then land on a runway to be unloaded and refurbished for subsequent flights.

WINK will consist of three full-scale Crystal Eye pixels and their anticoincidence system, enabling technology demonstration for a future full-scale mission. WINK crystals, made from LYSO material, are used to enhance the visibility and performance of technologies. WINK will observe deep space and Earth, hunting for Gamma-Ray Bursts (GRBs) and Terrestrial Gamma-ray Flashes (TGFs), respectively. The designated position for WINK in the Multi-Purpose Cargo Bay (MPCB) of Space Rider will ensure a 30° field of view (FOV). Fig. 3 shows Space Rider and a mechanical scheme of WINK.

WINK will operate in three modes:

- **Space Observation Mode**: WINK will be exposed to deep space, characterizing the cosmic background at its orbit and hunting for GRBs.
- **Calibration Mode**: After each significant event, WINK will perform a one-minute calibration based on the emission spectrum detection of each crystal. We will use

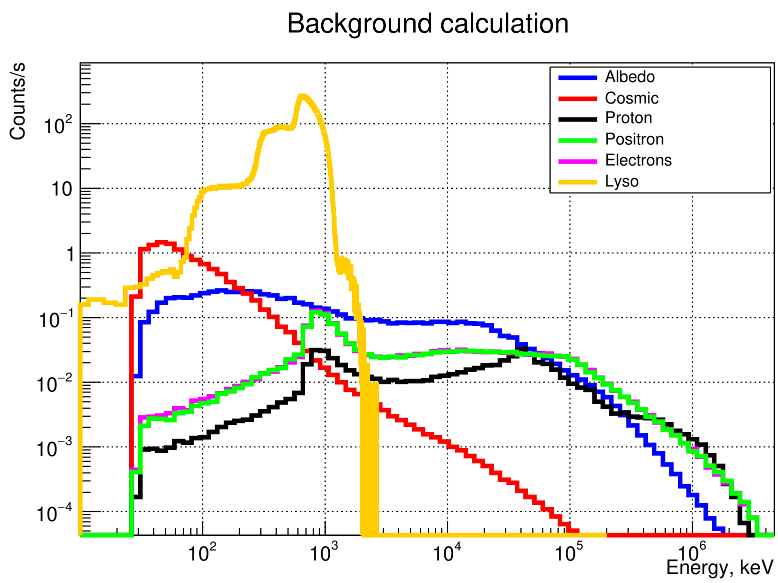

Fig. 4. – Background in the Low Earth Orbit (LEO) for: albedo photons (blue), cosmic photons (red), albedo and cosmic protons (black), albedo and cosmic positrons (green) and albedo and cosmic electrons (green) + LYSO background. From [7]. More details in the text.

the LYSO emission spectrum, which, as mentioned above, has several peaks of known energies. If no relevant events occur, this calibration will be conducted every 30 minutes.

- **Earth Observation Mode**: WINK will point towards Earth to hunt for Terrestrial Gamma-ray Flashes.

As we said, CE is intended to operate at an altitude of 550 km, in an orbit with an inclination of $\sim 20°$. Therefore the spacecraft is assumed to transit relatively low-background equatorial regions, away from the South Atlantic Anomaly [9] and the poles. The dominant background radiation can then be assumed to be of cosmic origin and secondary products of this radiation with the atmosphere. To model the background spectra in this particular orbit, different parametric functions for each background are assumed from [7]. The main radiation and particle backgrounds are reported in Fig. 4, and include: cosmic diffuse γ-ray photons (red), albedo X-ray and γ-ray photons (blue), trapped protons (black), trapped positrons (green), electrons (purple) and LYSO (orange). This background was obtained under the condition that at least one pixel or even the anticoincidence system within our FOV was triggered (with deposited energy greater than 0).

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