PROCEEDINGS OF SCIENCE

EPSI R&D: Developing an Innovative Electron-Positron Discrimination Technique for Space Applications

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Sixteen years after the first detection of the cosmic positron excess, its origin remains uncertain. Understanding this phenomenon is crucial not only for astrophysics but also for fundamental physics, as it represents one of the most compelling potential signatures of dark matter. To clarify the nature of the positron excess, it is essential to independently extend the measurements of electron and positron fluxes beyond a few hundreds of GeV. In the near term, this cannot be achieved with the conventional approach based on a magnetic spectrometer, but it is necessary to develop an innovative charge-sign discrimination technique suitable for calorimeter-based space experiments. The Electron Positron Space Instrument (EPSI) is a two-year R&D project designed to explore the feasibility of distinguishing electrons from positrons in space by exploiting synchrotron photons emitted as charged particles propagate through Earth's magnetic field. Achieving this goal requires the development of a cost-effective X-ray detector optimized for high efficiency in the low-energy range, while remaining scalable to large detection areas. This contribution outlines the project's core concept and provides an overview of the status of the ongoing activities.

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1. Introduction

The quest for direct or indirect signatures of dark matter remains one of the foremost experimental challenges in modern particle physics. Despite decades of intense effort, no definitive evidence has been obtained. Among the most intriguing potential hints is the so–called positron excess [1–3], first revealed by the PAMELA experiment. Current measurements, however, do not allow a firm interpretation, since the observed signal may also originate from conventional astrophysical sources such as nearby pulsars or supernova remnants. To rigorously test the dark matter hypothesis, it is necessary to extend the measurements of the electron and positron fluxes to energies well above several hundreds of GeV. Such measurements would also strongly impact cosmic–ray physics, given the cutoff in the inclusive electron+positron spectrum around 1 TeV [4, 5]. At these energies, the presence of local sources can be revealed by the observation of distinctive spectral features.

The existing detection techniques are not yet capable of probing well beyond a few hundreds of GeV. Magnetic spectrometers face severe technological constraints at high energies, while calorimeter–based instruments, though effective in this regime, are inherently unable to determine the particle charge. Consequently, in order to separately measure the electron and positron spectra, it is essential to devise a novel charge–sign discrimination technique that can be deployed as an auxiliary detector on calorimeter experiments. This is precisely the objective of the Electron Positron Space Instrument (EPSI), a two–year R&D project launched in 2023 under the program PRIN (*Progetto di Rilevante Interesse Nazionale*) and funded by European Union recovery funds.

2. Detection method

The EPSI concept relies on distinguishing electrons from positrons in orbit by detecting both the particle itself and the synchrotron photons it emits while traveling through the geomagnetic field. In the relativistic limit, the particle deflects only slightly, and the synchrotron radiation is emitted in a narrow cone nearly tangent to its trajectory. Considering a plane perpendicular to the propagation axis, the synchrotron photons will always be emitted on the side opposite to the particle's curvature. As shown in Fig. 1, by knowing the field configuration, the charge sign of the incoming particle can be inferred by reconstructing both the particle track and the synchrotron photon impact points.

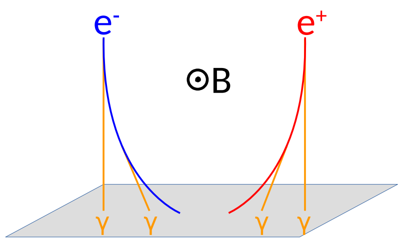


Figure 1: Concept of charge sign determination based on the simultaneous detection of a particle (electron or positron) and the synchrotron photons emitted during its propagation in a constant magnetic field.

The use of synchrotron radiation for cosmic–ray studies in space was first suggested by Prilutskii in 1972 [6] and later elaborated in [7]. Since then, several balloon and satellite experiments have investigated it as a primary or complementary technique (see [8, 9] for references). The EPSI project differentiates itself in two aspects. First, earlier studies mainly aimed to use synchrotron photons to indirectly infer particle energies, whereas EPSI focuses on charge sign discrimination as an auxiliary system to a large–acceptance calorimeter, ideally extending measurements to multi–TeV energies.

Second, modern detector technologies allow the realization of synchrotron radiation detectors with significantly improved performance and reduced cost compared to past designs.

3. Instrument requirements

An example of a possible detector configuration is shown in Fig. 2. The electromagnetic calorimeter (ECAL) is responsible for measuring the particle energy and trajectory, suppressing the proton background, and providing the main trigger of the instrument. Following the Calocube design concept [10–13], it may consist of CsI:Tl cubic crystals coupled to photodiodes. On the ECAL's opposite faces, the synchrotron radiation detector (SRD) records the photons emitted by the incoming particle, thus enabling charge sign discrimination. Designing such a detector is technologically demanding, and represents the central challenge of the EPSI project.

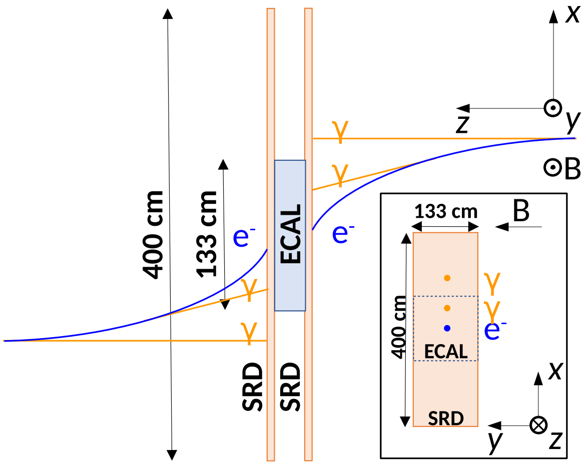


Figure 2: A simple implementation of the EPSI space instrument composed by ECAL and SRD detectors. Two electrons from opposite directions, perpendicular to the geomagnetic field, are shown.

For illustration, consider the case of a 1 TeV electron propagating perpendicular to a 0.4 G magnetic field, initially aligned with the normal to the detector surface. In this case, one expects an average of $< N >= 4.5$ synchrotron photons reaching the detector, with a critical energy ϵ_c = 26.8 keV and a position spread $\sigma = 9.3$ mm. This implies that the SRD must achieve an efficiency greater than 80% below 100 keV (ideally down to 1 keV) while remaining cost–effective for large areas. To suppress the astrophysical X–ray background, a segmentation scale of ~ 1 $cm \times 1$ cm is required, and a response time of a few hundreds of ns is desirable. On the other hand, fine energy resolution is unnecessary, since photon position is enough for charge identification.

4. SRD development

Given the required large detection area, semiconductor devices are not cost–effective in the soft X–ray range. A more viable approach is the use of thin scintillators, wrapped with reflective coatings and coupled to SiPMs. The main challenge lies in maximizing light collection while ensuring that the entrance window remains transparent to X–rays down to 1 keV. A promising solution is to employ a thin aluminum layer (a few hundred nm thick), which offers $\sim$ 95% optical reflectivity with negligible X–ray absorption. While Al sputtering has been tested in our laboratory, current efforts concentrate on optimizing the scintillation cell design using commercial coatings. Here we give a short description of the development and characterization of the single detection unit. For a better discussion of this topic, please refer to the paper [14].

The area of the detection cell was chosen to be 2 $cm \times 2$ cm, as a compromise between the segmentation needed to identify the charge sign and a reasonable number of readout channels. The SiPM is mounted at the center of the face that is opposite to the one exposed to incoming X–rays.

As shown in Fig. 3, optical ray–tracing simulations indicate that a thickness of 3 mm maximizes the fraction of detected scintillation photons by minimizing the losses due to self–absorption and edge transmission. The commercial coatings most suited for this application is the Enhanced Specular Reflector (ESR), with a reflectivity larger than 98%, which was used to completely wrap the crystal. Among SiPMs, the Hamamatsu MPPC S13360-6075PE leads to the largest signal, thanks to a photon detection efficiency (PDE) of 40% at 550 nm, an area of 6 $mm \times 6$ mm and a contained dark count rate of 2 MHz. Ideally, the scintillator must have a high light yield (LY) and CsI:Tl is a good candidate with its 54 ph/keV. An even better solution is GAGG:Ce, which has a similar light yield but much shorter decay constant of 100 ns, even if it is more expensive. A picture of a prototype for the single detection cell tested in our laboratory is shown in Fig. 4.

Signal readout is performed with a simple setup based on an amplifier connected to CAEN DT5790, a 250 MS/s 12-bit waveform digitizer with charge integration capability. Calibration is carried out in units of *micro channel on* (*m.c.o.*), *i.e.* the number of SiPM cell that contributed to the signal. This *ADC/m.c.o.* calibration factor is extracted by fitting the dark count spectrum with a multi-gaussian function, as shown in Fig. 5a. Radioactive sources are then used to characterize the response, integrating the waveform over a sufficiently long interval to collect at least 85% of the total charge. As an example, Fig. 5b shows the spectrum obtained using a ^{133}Ba source. For each spectral line, gaussian fits provide the mean value and the standard deviation, assuming a polynomial function for the Compton background.

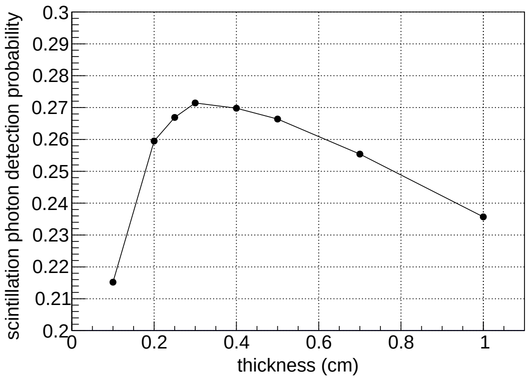


Figure 3: Simulated scintillation photon detection probability, *i.e.* the fraction of scintillation photons that generate a signal in the SiPM, versus crystal depth for a 2 $cm \times 2$ cm CsI:Tl scintillator coupled to MPPC S13360-6075PE.

Fig. 5c shows the average number of *m.c.o.* generated by the photoelectric interaction of the incident X-ray per *keV* of absorbed energy, as a function of the energy itself. Considering the systematic uncertainties, the CsI:Tl system is well linear below 100 keV, the relevant range for this application, while deviations at higher energies arise from the non–linear light yield of the crystal itself. The measured value, of about 15 $m.c.o./keV$, corresponds to a light collection efficiency of about 50%, after taking into account LY, PDE, and cross–talk coefficients.

Fig. 5d shows the energy resolution, as a function of the energy itself, fitted with the following parametrization: $\sigma_E/E = \sqrt{p_0^2 + (p_1/\sqrt{E})^2 + (p_2/E)^2}$. At high energies, the energy resolution is dominated by the irreducible constant term p_0, arising from non–uniformity and non-proportionality of crystal response. At low energies, the performances are limited by the noise term p_2, which is mainly due to dark count contributions. In order to enlarge the detection window down to 1 keV, it is therefore necessary to significantly decrease this effect by cooling down the sensor.

Another key activity necessary to reach the low energies is to find a better material to wrap the crystal on the X-ray entrance face. Here, ESR must be replaced with a very thin foil that minimizes self-absorption of low energy X-rays. Preliminary tests show that a thin aluminized Mylar film is an excellent candidate for this purpose. This solution leads to a good X-ray transparency without a significant loss in optical reflectivity, reducing the final $m.c.o./keV$ factor by about 50%.

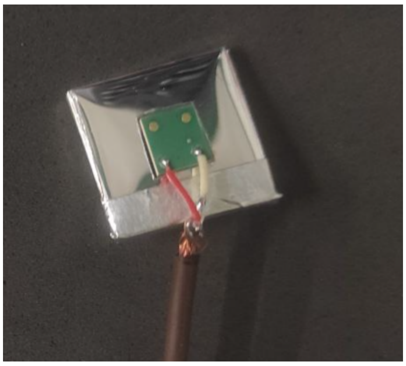
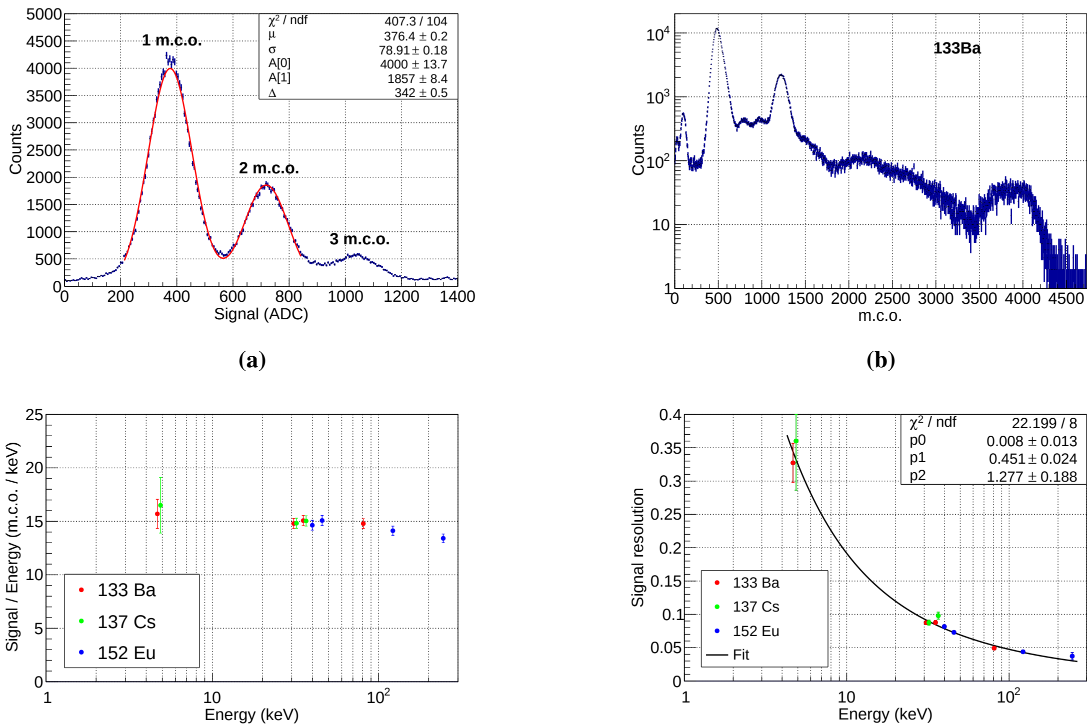


Figure 4: Picture of the CsI:Tl detection cell prototype used for the result discussed in the text.



(a) **(b)** **(c)** **(d)**

Figure 5: Results from the CsI:Tl prototype under test [14]: (a) example of the dark count distribution used to calibrate the SiPM gain, (b) example of the spectrum obtained with a ^{133}Ba source, (c) average photoelectric signal per unit of energy deposit, (d) energy resolution of the detection cell.

5. Summary

The EPSI project, started in 2023 as a PRIN with EU recovery funding, aims to develop a novel charge–sign discrimination technique that can be used by an auxiliary detector in calorimeter–based cosmic–ray experiments. Current work focuses on optimizing the single–cell synchrotron radiation detector. While many design parameters have been established through laboratory tests, upcoming efforts will address the optimization of the entrance window to extend sensitivity down to 1 keV. Once finalized, attention will shift toward the integration of the full instrument, emphasizing reconstruction performance and background rejection.

6. Acknowledgments

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References

[1] Adriani, O., *et al.* (PAMELA Collaboration), *Nature* **458.7238** (2009) 607

[2] Ackermann, M., *et al.* (Fermi Collaboration), *Phys. Rev. Lett.* **108.1** (2012) 011103

[3] Aguilar, M., *et al.* (AMS-02 Collaboration), *Phys. Rev. Lett.* **122.4** (2019) 041102

[4] Alemanno, F., *et al.* (DAMPE Collaboration), *Nature* **552.7683** (2017) 63-66

[5] Adriani, O., *et al.* (CALET Collaboration), *Phys. Rev. Lett.* **131.19** (2023) 191001

[6] Prilutskii, O. F., *Soviet Journal of Exp. and Theor. Phys. Lett.* **16** (1972) 320-321

[7] Stephens, S. A., *et al.*, *J. Geophys. Res. Space Phys.* **88.A10** (1983) 7811-7822

[8] Adriani, O., *et al.*, *Proceedings of Science* **476** (2024) 692

[9] Adriani, O., *et al.*, *JINST* **20.07** (2025) C07045

[10] Adriani, O., *et al.* (Calocube Collaboration), *JINST* **14** (2019) P11004.

[11] Adriani, O., *et al.* (Calocube Collaboration), *JINST* **17** (2022) P08014.

[12] Adriani, O., *et al.* (Calocube Collaboration), *JINST* **16** (2021) P10024.

[13] Adriani, O., *et al.* (Calocube Collaboration), *NIM A* **1061** (2024) 169079

[14] Adriani, O., *et al.* (EPSI Collaboration), *Particles* **8** (2025) 101