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The Ziré experiment on board of the NUSES mission

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Abstract. NUSES is a new space mission aiming to test innovative observational and technological approaches related to the study of low energy cosmic and gamma rays, high energy astrophysical neutrinos, Sun-Earth environment, Space weather and magnetosphere-ionosphere-lithosphere coupling (MILC). The satellite will operate on a low-Earth and sun-synchronous polar orbit, and will host two payloads: Terzina and Zirè. Zirè will perform measurements of electrons, protons and light nuclei from a few up to hundreds MeV, also testing new tools for the detection of cosmic MeV photons (e.g. for GRBs). Innovative technologies for space-based particle detectors will be adopted and tested thus increasing the corresponding Technology Readiness Levels (TRL) of the adopted solutions. The light readout system (from plastic scintillators and crystals) will be entirely provided by Silicon Photo Multipliers (SiPMs), thus ensuring a compact and light design. In this work, a general overview of the Zirè payload will be given.

The NUSES mission is an Italian-led initiative to advance innovative technologies and observation methods for space-based measurements of cosmic and gamma rays, as well as high-energy astrophysical neutrinos. This collaborative project involves the Gran Sasso Science Institute (GSSI), the Istituto Nazionale di Fisica Nucleare (INFN), the Italian Space Agency (ASI), multiple Italian universities, the University of Geneva, and the University of Chicago. The mission is supported by Thales Alenia Space Italy (TAS-I), which provides the modular 2MF/NIMBUS (New Italian Micro BUS) satellite platform. Managed by ASI, the satellite is scheduled for launch in 2026. It will operate in a Low Earth Orbit (LEO) at an altitude of 535 km, with a high inclination of 97.8° (LTAN = 18:00), in a Sun-synchronous orbit along the day-night terminator.

The satellite will carry two payloads: Zirè [1] and Terzina [2]. Zirè is tailored to study cosmic particles, including electrons, protons, and light nuclei with $E < 300\,\mathrm{MeV}$, originating from solar and galactic sources. It will monitor cosmic radiation variability, such as changes in the Van Allen belts, and investigate potential links with seismic activity through the Magnetosphere-Ionosphere-Lithosphere Coupling (MILC). Moreover, Zirè will detect photons in the 0.1–30 MeV range, probing transient and persistent gamma-ray sources while contributing to advanced sensor development. Terzina, instead, will measure atmospheric Cherenkov light detection from space, paving the way for ultra-high-energy cosmic ray and neutrino astronomy.

The optical readout for both payloads relies on Silicon Photo Multipliers (SiPMs), offering a compact design, reduced power consumption, and enhanced performance compared

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to traditional PhotoMultiplier Tubes (PMTs). SiPM-based technology is a pivotal aspect of the mission. This paper focuses on the scientific objectives and instrumentation of the Zirè experiment.

1 The Zirè Experiment

The primary goal of the Zirè experiment is the detection of Cosmic Rays with energies from a few MeVs to hundreds of MeVs [3]. Beyond characterizing their spectral properties, Zirè aims to investigate anomalies in their flux, potentially associated with natural terrestrial events like earthquakes, volcanic eruptions, or intense Gamma Ray Bursts (GRBs).

Prior experiments in Low Earth Orbit (LEO) and on the ground have revealed unusual ionospheric phenomena, including electromagnetic and plasma density perturbations, as well as rises in low-energy particle counts in the Van Allen Belts (VABs). These observations align with the Magnetospheric-Ionospheric-Lithospheric Coupling (MILC) model [4]. Zirè will also monitor Galactic Cosmic Rays and solar particle emissions, particularly those below 10 GV rigidity, which are significantly influenced by solar activity. These include periodic phenomena, such as the 11-year solar cycle, and transient events like solar flares and Coronal Mass Ejections (CMEs), which emit Solar Energy Particles (SEPs) with energies ranging from tens of keV to several GeV. SEPs contribute to space weather effects, including geomagnetic storms.

Additionally, Zirè will detect photons in the 0.1–30 MeV range, enabling the study of transient events like GRBs, electromagnetic counterparts to gravitational wave (GW) events, and persistent gamma-ray sources. Correlations between GRBs and local effects on charged particles may also be explored [5].

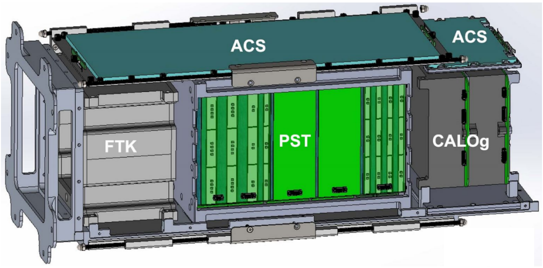
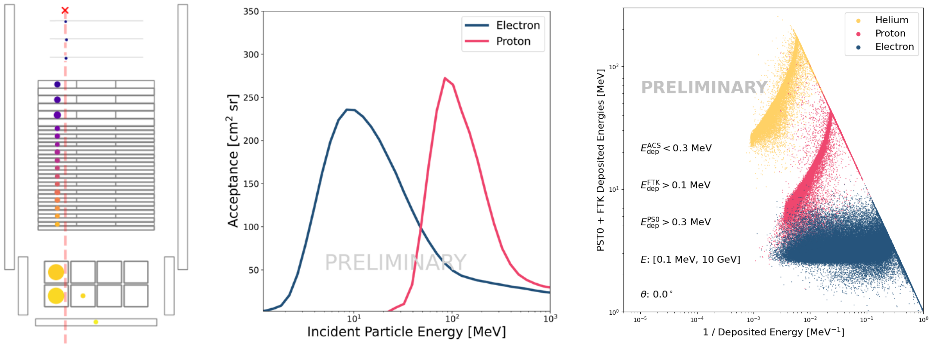


Figure 1. Mechanical design of the Zirè detector. Charged particles enter through a thin window (left). Gamma rays are measured via additional windows near the CALOg in horizontal (H) and zenith (V) directions. The LEM sub-detector is not shown.

The Zirè detector is shown in Figure 1, its key components include: a Fiber Tracker (FTK), 3 X-Y modules with $9.6 \times 9.6\,\mathrm{cm}^2$ cross-section and 2.5 cm spacing. Each module consists of two orthogonal planes of double-layer polystyrene-based fibers, designed to minimize Coulomb scattering and energy loss [6]. A Plastic Scintillator Tower (PST), a tower of 32 layers, with the first six layers sized $12 \times 12 \times 1\,\mathrm{cm}^3$ and the remaining 0.5 cm thick. These layers follow the FTK for additional particle tracking and energy measurement. A Calorimeter (CALOg), a $4 \times 4 \times 2$ matrix of crystals ($2.5 \times 2.5 \times 3\,\mathrm{cm}^3$). Two materials are considered: Lutetium-Yttrium Oxyorthosilicate (LYSO) and Gadolinium Aluminum Gallium Garnet (GAGG), offering high light yield and fast response times. An Anti-Coincidence System (ACS), nine 0.5 cm-thick plastic scintillator tiles surround the instrument to reject charged particles entering near the CALOg and the PST.

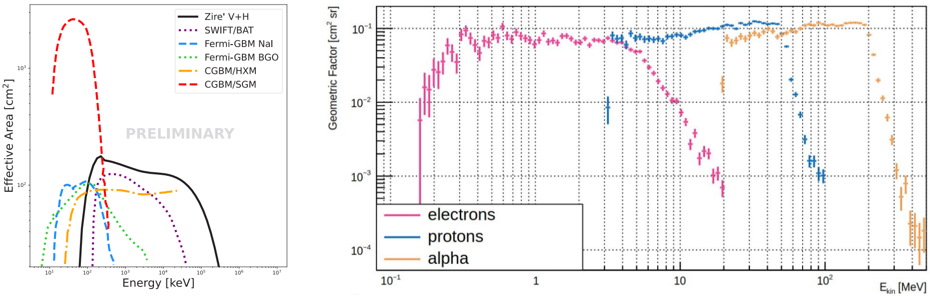
The detector's FTK, PST, and CALOg are oriented toward the celestial horizon. Charged particles enter through the FTK window. Two windows are placed near the CALOg: one pointing toward the horizon (H) and the other toward the zenith (V). This configuration enhances gamma-ray sensitivity by suppressing background charged particles.



(a) (b) (c)

Figure 2. a: Simulated 1 GeV proton event in Zirè. The dashed red line traces the primary particle track. **b:** Effective acceptance for protons (red) and electrons (blue). **c:** Particle identification via energy deposition patterns for simulated electron, proton, and helium events.

Monte Carlo (MC) simulations using Geant4 [7] were conducted to evaluate the detector's performance. Figure 2b shows preliminary acceptance estimates for protons and electrons, requiring a 0.1 MeV energy deposit in the FTK and 0.3 MeV in the PST's first layer (PS0) with full containment. Particle identification (PID) was achieved by analyzing energy deposit correlations across sub-detectors, as shown in Figure 2c.



(a) (b)

Figure 3. a: Effective area for gamma detection compared to Fermi-GBM, CALET-GBM, and SWIFT/BAT. **b:** Geometrical factor for electrons, protons, and alphas in Zirè's Low Energy Module (LEM) [8].

The CALOg independently measures gamma rays in the 0.1–50 MeV range through two dedicated windows (see Figure 1). Preliminary effective area estimates, shown in Figure 3a, highlight performance trends influenced by LYSO/GAGG absorption properties.

A specialized Low Energy Module (LEM) [8] extends Zirè's capabilities to lower-energy particles, such as electrons ($E < 7$ MeV) and protons (3–50 MeV), enhancing sensitivity to MILC-related phenomena. The LEM employs silicon detectors, a plastic calorimeter, veto systems, and a scintillating collimator for directional particle reconstruction. Geometrical factors for electrons, protons, and alphas are shown in Figure 3b.

2 Conclusions

In this study, we introduced the NUSES mission and one of its two scientific payloads, Zirè. The Zirè detector will facilitate the exploration of low-energy Galactic Cosmic Rays (GCRs) and gamma radiation in the keV–MeV range.

This instrument embodies significant advancements in space-based detector technologies, with the incorporation of Silicon Photomultipliers (SiPMs) marking a notable step forward. These innovations not only enhance the capabilities of space observatories but also offer meaningful contributions to ongoing research in astroparticle physics, paving the way for future discoveries.

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