IL NUOVO CIMENTO **43 C** (2020) 117
DOI 10.1393/ncc/i2020-20117-1

Communications: SIF Congress 2019

HERD: The High Energy cosmic-Radiation Detector

D. Kyratzis(1)(2)(*)(**)

(1) *Gran Sasso Science Institute - Viale Francesco Crispi 7, 67100 L'Aquila, Italy*
(2) *INFN, Laboratori Nazionali del Gran Sasso (LNGS) - 67100 Assergi, L'Aquila, Italy*

received 31 January 2020

Summary. — An overview of the High Energy cosmic-Radiation (HERD) detector will be presented, as one of the prominent instruments to be installed onboard the upcoming Chinese Space Station (CSS). Primary scientific goals regarding this initiative include: precise measurements of the cosmic-ray (CR) energy spectra and mass composition, at energies up to the PeV range; contributions to high-energy gamma-ray astronomy and transient studies; as well as indirect searches for Dark Matter (DM) particles via their annihilation/decay to detectable products. HERD is configured to accept incident particles from both its top and four lateral sides. Specifically considering its initial setup, HERD comprises a homogenous calorimeter, conceived as an octagonal prism of LYSO cubic crystals, subsequently enclosed by layers of silicon trackers and plastic scintillator detectors, thus finalized with the instrumentation of a transition radiation detector on one of its lateral faces. In that sense, an order of magnitude increase in acceptance (regarding previous missions) is foreseen, owing to its pioneering design. Continuous updates and beam tests validate HERD's capabilities, while varying configurations are tested in order to optimize its performance.

1. – Introduction

From their discovery up to the current era, cosmic rays (CRs) established the investigation of fundamental particle physics, more than 40 years prior to the advent of high-energy particle accelerators. A substantial amount of elementary or composite particles were initially identified in CRs, leading to a clarified picture of the microscopic world and its intrinsic interactions.

Throughout an extended time interval, CRs remain in the forefront of intense research activities, manifested by a plethora of sophisticated experiments that probe their nature

---

(*) On behalf of the HERD Collaboration.
(**) E-mail: `dimitrios.kyratzis@gssi.it`

of origin, acceleration and propagation in the Universe. Although crucial information has been well received from indirect (ground-based) CR experiments over the years, there is an imminent need to explore highly energetic CR particles and gamma-rays by means of direct observations, carried out by space-borne detectors. In that way, refined results regarding distinct features in the energy spectra can be obtained, along with a consistent picture concerning the evolution of mass composition with energy.

Results considering the interpretation of recent CR data lead to a picture of Galactic CR nuclei being accelerated at supernova remnant (SNR) shocks by first-order Fermi mechanism [1] and subsequently injected into the Interstellar Medium (ISM), before leaving the Galaxy. That picture constitutes one of the most favorable scenarios, although conclusive results have yet to be derived. Additionally, a major unresolved issue regarding hadronic CRs is the so-called "knee", a prominent feature that marks a spectral steepening of E^{-3} at particle energies of few PeV. Traditionally, highly-energetic particle regions were "accessible" only by indirect CR experiments, although with an inherent difficulty in performing composition studies with small systematic errors. On the contrary, direct CR experiments are capable of measuring both energy and charge of an incident particle, although due to CR fluxes rapidly decreasing with energy (and in conjunction with limited exposure of space-borne instruments), no statistically meaningful results could be inferred above few tens of TeV with current experiments.

Consequently, forthcoming space-based experiments should incorporate requirements related to: increased geometric factor ($>\mathrm{m}^2\mathrm{sr}$), extended mission duration ($\sim$5–10 yr), as well as high discrimination power in separating different cosmic radiation components. Combining the above-stated properties will result in exposure of about 15–20 $\mathrm{m}^2\mathrm{sr}$ yr, hence allowing for a deeper understanding of the intricate features that constitute distinctive structures in CR spectra.

In this regard, both gamma-ray observations and Dark Matter (DM) searches will benefit from such performance enhancement. Specifically, wide field-of-view (FOV) gamma-ray detectors in orbit will be able to contribute both in probing distinctive astrophysical objects and providing valuable insight considering the electromagnetic counterpart accompanying the detection of gravitational waves (GW), while supporting major ground-based narrow FOV (upcoming) telescopes, like the Cherenkov Telescope Array (CTA). On the other hand, the search for a possible DM candidate could be fulfilled by detecting its annihilation/decay products, that might lead to characteristic formation of spectral features in CR components or gamma-rays. Recent observations of electron and positron spectra [2-6] reveal possible hints, although these could fairly be interpreted by contributions of both astrophysical and DM sources.

Therefore, HERD was proposed to focus on the above-stated issues as one of the prominent instruments to be installed onboard China's Space Station (CSS), with a planned duration of 5 to 10 years. An international collaboration is established around the HERD initiative, involving researchers from China, Italy, Switzerland, Spain and more countries that are willing to contribute in this endeavor. In the following, a brief description of the HERD proposal will be given, along with an overview regarding primary scientific objectives and expected results.

2. – Detector description

In its baseline design [7] (shown in fig. 1), HERD is conceived around a 3-D cubic imaging calorimeter (CALO), made of approximately 7500 LYSO crystals that form an octagonal prism. This design ensures detection of incident particles from both its top and

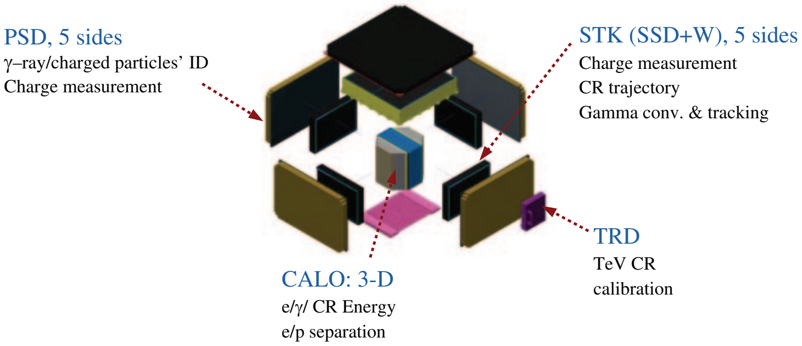


Fig. 1. – Exploded view of the baseline HERD design.

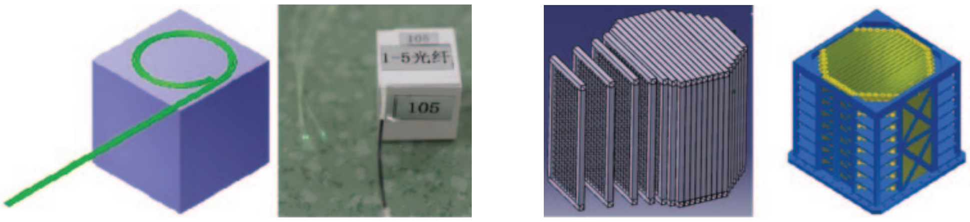
4 lateral sides, as well as satisfactory energy measurements and e/p separation. Microstrip silicon trackers (STKs) are situated on all active sides in order to obtain accurate tracking of impinging particles as well as measuring their charge. In its entirety, HERD is surrounded by a plastic scintillator detector (PSD), aiming to provide gamma-ray and charged particle triggers, together with an additional level of charge measurement. Finally, a transition radiation detector (TRD) is placed on one of the lateral faces in order to provide energy calibration of nuclei in the TeV region. Consequently, an increase of more that an order of magnitude in acceptance is obtained by utilizing optimized detector techniques, in a novel design fulfilling all physics requirements, while maintaining a manageable payload for a space mission.

HERD will be installed on the CSS (to be completed in 2022) around 2026, with a lifetime of 5–10 years. The instrument will follow a low-Earth orbit (LEO) at an altitude of approximately 340–450 km, with an inclination angle of 42°. Meticulous placement of the instrument on the CSS will ensure FOV of ±70°, while its payload will not exceed 4 tons in weight. Detailed specifications [8] and primary scientific objectives of HERD are presented in table I.

2˙1. *Calorimeter (CALO) specifications.* – HERD's calorimeter (CALO) comprises three subsystems: the crystal array, the intensified scientific CMOS (IsCMOS) camera and trigger subsystem. The crystal array is responsible of recording cascades

Table I. – *Main specifications of HERD.*

Item	Value
energy range (e)	10 GeV–100 TeV
energy range (γ)	0.5–100 TeV
energy range (nuclei)	30 GeV–3 PeV
angular resolution (e/γ)	0.1° @ 10 GeV
energy resolution (e)	1% @ 200 GeV
energy resolution (p)	20% @ 100 GeV–PeV
e/p separation	10^{-6}
geometric factor (e)	>3 m^2 sr @ 200 GeV
geometric factor (p)	>2 m^2 sr @ 100 GeV



(a) LYSO crystal with WLSF fibers (b) Assembly of the crystal array

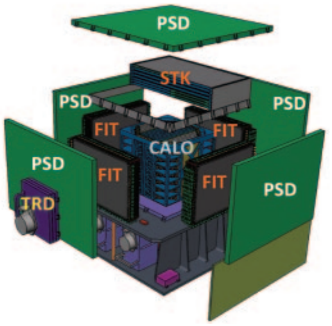
Fig. 2. – Instrumentation of LYSO crystals in subsequent arrays forming HERD's calorimeter.

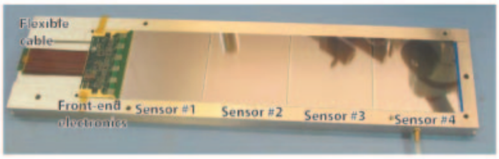
(electromagnetic or hadronic) induced by highly energetic particles as they impinge on each surface. Each one of the 7500 LYSO crystals constitutes a $3 \times 3 \times 3\,\mathrm{cm}^3$ cube (fig. 2(a)) with radiation length of approximately 1.14 cm (each crystal being $\sim 2.6\ X_0$ thick), resulting in an integrated calorimeter (fig. 2(b)) of 55 radiation lengths and 3 nuclear interaction lengths from all sides. Energy from the cascade sequence is deposited in the crystal array and converted to scintillation photons, which are subsequently transmitted via wavelength-shifting fibers (WLSF) to IsCMOS cameras (for frame readout) and the trigger system (providing common triggers to other instruments). Furthermore, an additional readout with photodiodes will be implemented and utilized in a fraction of the LYSO crystals. This fraction could be used for energy measurements of TeV–PeV protons and nuclei, allowing for a robust cross-calibration of the entire readout system and an effective reduction of systematic uncertainties.

Utilizing a small crystal is advantageous due to the possibility of obtaining detailed information concerning the shower development, thus leading to enhanced discrimination between electromagnetic and hadronic shower topologies. Moreover, having an increased light yield, fast decay time, short nuclear interaction length and low temperature coefficient, LYSO crystals constitute an optimal choice for space-borne applications.

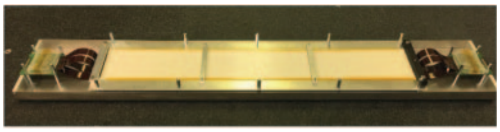
2˙2. *Silicon tracker (STK) configuration.* – The Silicon TracKer (STK) is designed to perform precise tracking of incident particles as well as to provide charge measurements of nuclei with $Z = 1$–26. In its initial design, HERD is composed of one top and four lateral STKs surrounding the calorimeter. The top STK is composed of six position-sensitive interleaved planes of silicon detectors, each one with an active area of $133 \times 133\,\mathrm{cm}^2$ and equipped with 28 Type-A ladders, instrumented with seven single-sided micro-strip silicon detectors (SSD). Lateral STKs in the initial HERD design (based on DAMPE [9], fig. 3(b)) comprise three position-sensitive interleaved planes of silicon detectors, each one with an active area of $95 \times 66.5\,\mathrm{cm}^2$ and equipped with 28 Type-B ladders, instrumented with five SSDs. Ladders on alternate planes are interleaved in order to provide precise measurements of the X and Y coordinates regarding the incoming particle.

For the lateral STK, requiring full acceptance imposes stringent constraints on placing front-end and readout electronics. Therefore, a viable idea would be to introduce a scintillating fiber tracker (FIT) [10] (fig. 3(a)), as an alternative to the silicon microstrip tracker, since fiber mats (fig. 3(c)) can be easily adapted to any desired geometry. As a consequence, the integrated dead area would be reduced (electronics placed outside the support trays, no gaps between sensors), while at the same time it could be less expensive to instrument additional layers, thus improving the point-spread function (PSF) of low-energy photons.





(b) STK ladder of DAMPE



(c) FIT module

(a) Alternative design with FIT geometry

Fig. 3. – Silicon tracker configuration in the alternative design with utilized silicon trackers (both STK and FIT).

2˙3. *The Plastic Scintillator Detector (PSD).* – The PSD of HERD will be utilized as an anti-coincidence detector (discriminating incident photons from charged particles), while providing charge measurement of incoming cosmic-ray nuclei in a range of $Z = 1$–26. Practically, thin and light materials (*i.e.*, organic scintillators) can be an optimal choice for this task. Moreover, scintillators featuring low density and good radiation hardness, while being affordable and available in mass production, seem as an intriguing choice for the PSD realization.

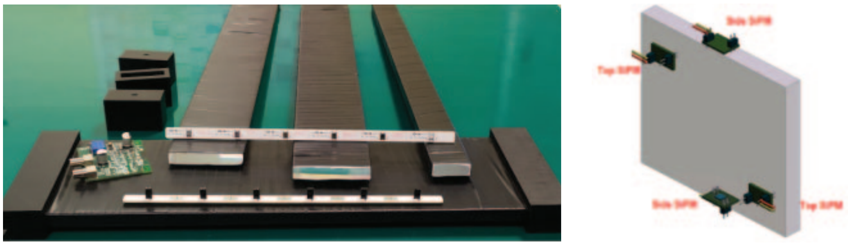
The main requirements concerning its design, include: high detection efficiency, broad dynamic range and good energy resolution. Two design layouts are currently investigated, one based on long scintillator bars (fig. 4(a)), the other on square (or rectangular) tiles (fig. 4(b)). Both configurations present advantages and disadvantages, mainly related to the optimal number of readout channels *vs.* back-splash [11] (or back-scattering) effects(1).

In its baseline design, the bar layout is composed of $170 \times 12 \times 1\,\mathrm{cm}^3$ scintillators for the top surface, while shorter bars ($120 \times 12 \times 1\,\mathrm{cm}^3$) are instrumented on the lateral sides. Scintillator bars are readout by silicon photomultpliers (SiPMs) on both ends instead of conventional PMTs, due to recent technological developments that demonstrate: fast light signal detection; good sensitivity to low light yields; lower power consumption and robustness. These features delineate the practicality and versatility of SiPMs in space applications, whereas PMTs require well-increased operation voltages ($\sim$kV) and lack robustness, therefore are not optimized for satellite experiments. Finally, alternating scintillator bars along the X and Y axes will be interleaved, in order to assist in track identification and charge measurement.

In the initial tile configuration [12], rectangular scintillators (10–15 cm/side and 1 cm thickness) are being tested in order to cover both top and lateral faces of the instrument, adopting a similar instrumentation technique to Fermi-LAT that provided satisfactory

---

(1) A small fraction of secondaries produced during electromagnetic showers in the calorimeter will drift backwards and eventually reach the PSD. Electron recoils produced via Compton scattering will act as a veto for incident gammas, thus decreasing the photon detection efficiency, especially at higher energies (>10 GeV).



(a) PSD bars (b) PSD tile scheme

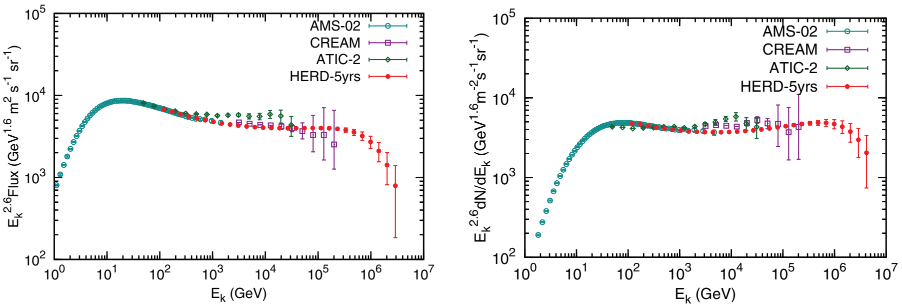
Fig. 4. – Evaluated configurations considering the PSD layout.

results in reducing back-splash effects. The total number of tiles in the baseline design amounts to 36 for the top and 64 for all lateral sides. Ongoing tests in both configurations aim to define the optimal scintillator type and size, SiPM model and quantity to be instrumented, along with the overall PSD placement.

3. – Scientific objectives and expected results

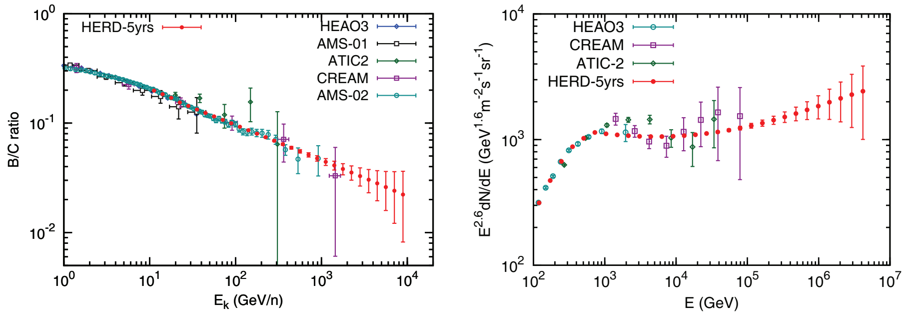
3˙1. *Perspectives on CR nuclei spectra.* – HERD will be capable of studying spectral features of various nuclei with optimal precision, up to the highest-achievable energies (considering space-borne instruments). Pronounced features, such as the “knee” [13] in the all-particle spectrum of hadronic cosmic-rays might be directly examined via light components such as protons and helium nuclei (as shown in fig. 5). In the usual picture, protons obtaining their maximum energy at galactic accelerators (*i.e.*, SNR shocks) are seemingly associated to a steepening of the spectrum, that constitutes the particle “knee” at an energy range of few PeV. On the other hand, heavier elements being less abundant than protons in the ISM will have a minor contribution below the knee that will gradually increase, due to sources accelerating particles rigidity-wise and not energy-wise.

Furthermore, open issues that can be addressed by HERD concern CR propagation in the Galaxy, a phenomenon that can be effectively probed by secondary-to-primary ratios (*i.e.*, B/C) as illustrated in fig. 6(a). Nuclei of secondary origin (Li, Be, B) are believed to be produced by primary CRs via spallation with the ISM. Detection



(a) Protons (b) Helium nuclei

Fig. 5. – HERD (expected) measurements of individual proton and helium energy spectra, based on a fit to AMS and ARGO-YBJ data [14] with 5 year exposure, compared with observations by AMS-02 [15, 16], CREAM [17] and ATIC [18].



(a) Boron-over-carbon ratio (B/C)

(b) Iron nuclei

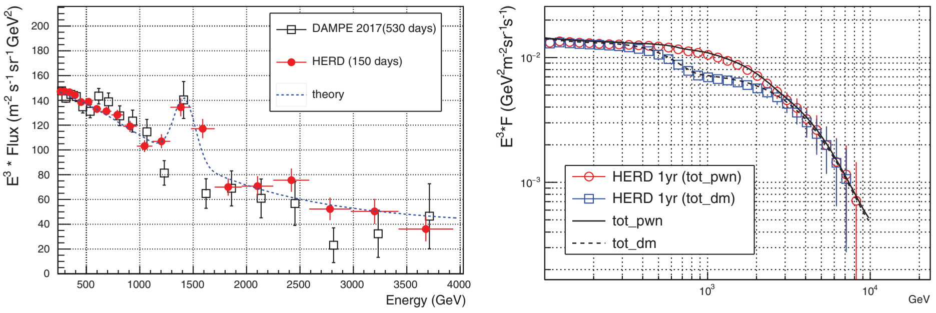
Fig. 6. – HERD expected measurements of B/C ratio and iron nuclei with a 5 year exposure, compared with observations by HEAO3 [19], AMS-01 [20], ATIC-2 [21], AMS-02 [22] and CREAM [23, 24].

of such secondaries in the multi-TeV region could provide insight on issues regarding spectral breaks of primary nuclei, thus clarifying possible explanatory scenarios (diffusive propagation origin or injection of CR spectrum in the ISM). Extending observations of spectral indexes regarding identification of individual species (up to ≈ iron) at the highest-achievable energies is a major task to be addressed by HERD (fig. 6(b)), along with searches of possible anisotropy hints in the CR spectra.

3˙2. *Fine structure of the all-electron spectrum.* – The all-electron component (e^+e^-) comprises 1% of total CRs, with a spectrum well described by a single power-law, consistent with recent measurements. Initially, ground-based Imaging Atmospheric Cherenkov Telescopes (IACTs) HESS [25] and VERITAS [26] had shown hints of a spectral break in the $e^+ + e^-$ spectrum near the TeV range, with VERITAS extending its results up to 20 TeV. In 2017, DAMPE [4] published results regarding the all-electron spectrum up to 5 TeV with great precision, leading to the first direct evidence of a spectral break at ≈1 TeV, with its existence being subsequently validated by CALET [27]. The aforementioned electrons experience energetic losses during propagation, which in addition to the CR diffusion coefficient value (extracted by B/C measurements) leads to an estimation of their production origin, within approximately 100 pc (local neighborhood).

In that sense, HERD will be able to probe these features —with high precision— and extend its measurements up to 100 TeV, due to its unprecedented acceptance. Moreover, HERD will be able to distinguish particles originating from astrophysical sources over possible dark matter annihilation products, due to inherent differences in both spectra. Generally, the distribution of particles produced in astrophysical sources follows an exponential cut-off, which is softer than the one caused by annihilation near the DM mass, which induces a "bump" (fig. 7(b)) at the e^+e^- spectrum. Finally, if a single, nearby source contributes to the observed CR e^+e^- spectrum from a specific direction, this effect could (in principle) generate a measurable anisotropy. Taking into account the almost isotropic contribution of electrons/positrons from DM annihilation (due to flat DM density distribution near the solar system), an observed anisotropy could demonstrate its astrophysical origin.

3˙3. *Gamma-ray observations.* – HERD will be providing insight on various unresolved topics in gamma-ray astrophysics, throughout a broad energy range (tens of GeV to several TeV) owing to its wide field-of-view (fig. 8). Primary objectives in this regard



(a) (b)

Fig. 7. – All-electron simulated spectra. Specifically, (a) presents a notable feature possibly detected by DAMPE at ∼1.4 TeV, that could be examined by HERD in 150 days of operation, while (b) illustrates HERD's foreseen capabilities in distinguishing a soft spectrum (pulsar) over a bump-like spectral feature (dark matter) with 1 year of data.

are: probing galactic and extra-galactic gamma-ray origins of diffuse emission; resolving the nature of unidentified sources; studying the mechanism of particle acceleration in astrophysical sources; as well as providing valuable information in transient studies concerning coherent observation of electromagnetic counterparts, triggered by gravitational waves (GWs) as seen by Advanced LIGO and Virgo. In that sense, complementary studies between space-borne and ground-based experiments are feasible, especially when taking advantage of the synergy between the aforementioned detectors. More importantly, exploiting the connection between HERD and ground-based γ-ray observatories will allow for simultaneous coverage of sources in the energy range of few GeV to PeV with substantial overlap of measured spectra (fig. 8). In that sense, achieving high spatial resolution will assist in distinguishing diffuse from localized contributions, considering acceleration and propagation mechanisms in supernova remnants, pulsar wind nebulae, pulsars and extended objects like Fermi bubbles.

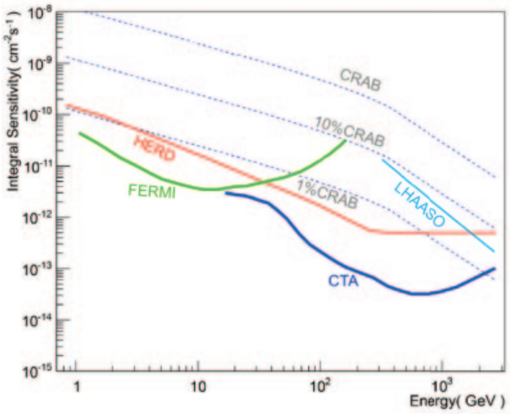


Fig. 8. – Expected gamma-ray sky sensitivity (5σ) regarding one year of data-taking with HERD. These results are compared with Fermi-LAT, LHAASO (both considering 1 year of observations) and CTA (50 hours). The HERD design of five active sides, surrounded by seven STK layers, is employed for the results illustrated above.

4. – Conclusions

The HERD detector will be installed onboard CSS on 2026, with a lifetime of 5–10 years. The main scientific objectives regarding this initiative reside in the fields of CR physics, gamma-rays and (indirect) DM searches.

Regarding CRs, HERD will be capable of providing high-precision measurements including single-element spectral indexes along with spectral hardenings/softenings of nuclei ranging from hundreds of GeV/nucleon to hundreds of TeV/nucleon. Especially for protons and helium nuclei, these measurements can extend up to PeV energies and possibly investigate the "knee" in hadronic CRs, for the first time via direct observations. Additionally, relevant goals include precise measurements of secondary-to-primary ratios (*i.e.*, B/C) in an extended energy range, that provide valuable insight on CR propagation in the Galaxy. Considering electrons and positrons of cosmic origin, respectively, great effort will be invested in probing fine structures in the leptonic component (e^+e^-), especially at the highest-achievable energies with great precision. Consequently, postulated contributions of nearby sources can be adequately examined, while concurrently searching (indirectly) for possible signatures of DM particle annihilation/decay in the all-electron spectrum. HERD will also be involved in high-energy gamma-ray observations throughout a broad energy range due to its wide FOV, as well as assisting in observations of ground-based experiments with an inherently narrow FOV.

The aforementioned objectives will be examined by a novel detector, which in its baseline configuration comprises a deep 3-D calorimeter (55 X_0, 3 Λ_I), structured as an octagonal prism of LYSO crystals (CALO), well surrounded by layers of micro-strip silicon trackers (STK) and ultimately covered by interleaved layers of plastic scintillators (PSD). Finally, a transition-radiation detector (TRD) will be situated on one of the lateral faces for the sake of TeV protons calibration. HERD's CALO will be able to provide precise energy measurement and e/p separation, the STK will specify particle tracks and measure the charge, while the PSD will ensure gamma-ray and charged-particle triggers as well as provide an additional level of charge measurement.

Utilizing state-of-the-art detector techniques with a pioneering design in HERD, an order of magnitude increase in acceptance can be attained, considering previous missions. Combining its acceptance with an increased lifetime leads to exposure times of approximately 15–20 m^2 sr yr, hence allowing for a precise examination of the above-stated goals.

Continuous development of the baseline design led to various alternatives and modifications, few of them being noted: tracker-in-calorimeter (TIC) concept; complementary calorimeter readout with photodiodes; fiber trackers (FIT). All of the above-mentioned alterations are being carefully examined and verified via simulations and beam tests, in order to provide the most optimized configuration of HERD.

* * *

The author would like to thank all members of the HERD Collaboration for supporting this work with valuable comments and fruitful discussions.

REFERENCES

[1] Fermi E., *Phys. Rev.*, **75** (1949) 1169.
[2] Aguilar M. *et al.*, *Phys. Rev. Lett.*, **113** (2014) 221102.
[3] Adriani O. *et al.*, *Riv. Nuovo Cimento*, **40** (2017) 473.

[4] Abdollahi S. *et al.*, *Phys. Rev. D*, **95** (2017) 082007.

[5] Ambrosi G. *et al.*, *Nature*, **552** (2017) 63.

[6] Adriani O. *et al.*, *Phys. Rev. Lett.*, **120** (2018) 261102.

[7] Zhang S. N., Adriani O., Albergo S. *et al.*, *The High Energy cosmic-Radiation Detection (HERD) facility onboard China's Space Station.* in *Proc. SPIE, Space Telescopes and Instrumentation 2014: Ultraviolet to Gamma Ray*, Vol. **9144** (SPIE) 2014, p. 91440X.

[8] Xu M. *et al.*, *Monte Carlo Simulation of HERD Calorimeter.*, in *Proc. SPIE Int. Soc. Opt. Eng.*, Vol. **9144** (SPIE) 2014, p. 91443S.

[9] Chang J. *et al.*, *Astropart. Phys.*, **95** (2017) 6.

[10] Perrina C. *et al.*, *PoS*, **ICRC2019** (2019) 122.

[11] Moiseev A. A. *et al.*, *Astropart. Phys.*, **22** (2004) 275.

[12] De Benedittis A. *et al.*, *PoS*, **ICRC2019** (2019) 069.

[13] Kulikov G. V. and Khristiansen G. B., *JETP*, **635** (1958) 35.

[14] Guo Y. Q. and Yuan Q., *Chin. Phys. C*, **42** (2018) 075103, arXiv:1701.07136.

[15] Aguilar M. *et al.*, *Phys. Rev. Lett.*, **114** (2015) 171103.

[16] Aguilar M. *et al.*, *Phys. Rev. Lett.*, **21** (2015) 211101.

[17] Ahn H. S. *et al.*, *Astrophys. J.*, **714** (2010) L89.

[18] Panov A. D. *et al.*, *Bull. Russ. Acad. Sci. Phys.*, **73** (2009) 564.

[19] Engelmann J. J. *et al.*, *Astron. Astrophys.*, **233** (1990) 96.

[20] Aguilar M. *et al.*, *Astrophys. J.*, **724** (2010) 329.

[21] Panov A. D. *et al.*, *PoS*, **ICRC2007** (2007) 3.

[22] Aguilar M. *et al.*, *Phys. Rev. Lett.*, **117** (2016) 231102.

[23] Ahn H. S. *et al.*, *Astropart. Phys.*, **30** (2008) 133.

[24] Ahn H. S. *et al.*, *Astrophys. J.*, **707** (2009) 593.

[25] Aharonian F. *et al.*, *Astron. Astrophys.*, **508** (2009) 561.

[26] Archer A. *et al.*, *Phys. Rev. D*, **98** (2018) 062004.

[27] Adriani O. *et al.*, *Phys. Rev. Lett.*, **119** (2017) 181101.