Results from the first 8.5 years of operation with CALET

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Abstract

CALorimetric Electron Telescope, CALET, is an astroparticle physics experiment installed on the International Space Station. Its scientific objectives includes searching for possible nearby sources of high-energy electrons and dark matter signatures, as well as studying the details of galactic cosmic-ray acceleration and propagation in the Galaxy. CALET measures cosmic-ray electron and positron spectrum up to 20 TeV, gamma-rays up to 10 TeV, and nuclei up to 1000 TeV. Since its start of operation in October 2015, CALET has been accumulating scientific data without any major interruptions. In this paper, we present results from CALET's first 8.5 years of operation.

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1 Introduction

The CALorimetric Electron Telescope (CALET), operating aboard the International Space Station (ISS), is a space-based experiment designed to investigate high-energy cosmic phenomena. Launched on August 19, 2015, via Japanese H-IIB rocket and delivered to the ISS using the HTV-5 Transfer Vehicle, the instrument was installed on the Japanese Experiment Module Exposed Facility. The mission is a collaborative effort spearheaded by the Japan Aerospace Exploration Agency (JAXA), with participation from the Italian Space Agency (ASI) and NASA.

The primary objective of the CALET mission is to explore the origins of cosmic ray electrons and search for signatures of dark matter by measuring the energy spectrum of electrons and positrons (all-electrons) up to 20 TeV. The detector is designed to precisely measure the all-electron flux measurements, achieving an exceptional energy resolution of 2% above 20 GeV, alongside strong proton background rejection. Furthermore, the instrument can measure detailed energy spectra and relative avandances of nuclei, extending to the highest energies directly observed, offering valuable insights into galactic cosmic-ray acceleration and propagation mechanisms. In addition to charged particles, CALET is equipped to detect high-energy gamma-rays from 1 GeV to 10 TeV. The onboard CALET Gamma-ray Burst Monitor (CGBM) covers from the hard X-ray to the soft gamma-ray region between 7 keV and 20 MeV.

In this paper, we present the latest results from CALET, including the spectra of electrons, protons and nuclei after 8.5 years of operation aboard the ISS.

2 Instruments and the on-orbit performance

CALET features a fully active calorimeter with a thickness equivalent to 30 radiation-lengths for particles a t normal incidence. Figure 1 shows a schematic side view of the detector, overlaid with a simulated 1 TeV electron shower. The instrument comprises three key subsystems: a Charge Detector (CHD), a 3 radiation-length thick imaging Calorimeter (IMC), and a 27 radiation-length thick Total Absorption Calorimeter (TASC). Its field of view extends to approximately 45 degrees from the zenith, and it offers a geometrical acceptance of 1040 cm^{2}sr for high-energy electrons. The CHD consists of two orthogonal layers of hodoscopes, each made of 14 plastic scintillator paddles. It achieves excellent charge resolution, capable of distinguishing chemical elements from $Z = 1$ to $Z = 40$. The performance of the CHD was validated through beam tests at GSI [1] and CERN-SPS [2]. The IMC includes 7 tungsten plates interspersed between 8 double layers of 1 mm^2 cross-section scintillating fibers, which are oriented in orthogonal directions. The fibers are individually read out by multianode photomultiplier tubes. It provides fine granularity and imaging capabilities, enabling precise measurement of the initial stage of particle shower development and the determination of the particle's incident direction. The TASC is a homogeneous calorimeter comprising 12 layers of PWO (lead tungstate) logs. It is optimized to measure the total energy of incident particles while efficiently distinguishing between electromagnetic and hadronic showers. Each PWO log is equipped with hybrid silicon avalanche photodiode and silicon photodiode packages, providing a dynamic range of 10^6. This design allows the TASC to measure signals ranging from 0.5 MIPs (inimum Ionizing Particles) to 10^6 MIPs, corresponding to the energy deposition from a proton-induced 1000 TeV shower. A more detailed description of the instrument can be found in the Supplemental Material of Ref. [3].

Since the start of scientific operations in October 2015, CALET has continuously collected data without major interruptions. For an all-calorimetric instrument like CALET, precise energy calibration is crucial for ensuring accurate measurements. Each detector element is calibrated using non-interacting cosmic-ray protons and helium, accounting for temporal variations observed during long-term operations. Calibration uncertainties must be carefully evaluated and incorporated into the estimation of the actual energy resolution [4]. The detector's response has remained remarkably stable, with no degradation in performance since the beginning of operations.

3 Results

3.1 Electron + positron spectrum

For precise electron measurements, robust electron identification is essential due to the significantly higher proton flux, which is more than 1000 times greater than the electron flux above 1 TeV. The 30 radiation-length thickness and the imaging capabilities of the TASC and IMC enable effective differentiation between the shower profiles of electromagnetic and hadronic cascades. In the final electron sample, the residual proton contamination is less than 5% up to 1 TeV, and less than 10% in the 1–7.5 TeV region, while keeping a constant high efficiency of

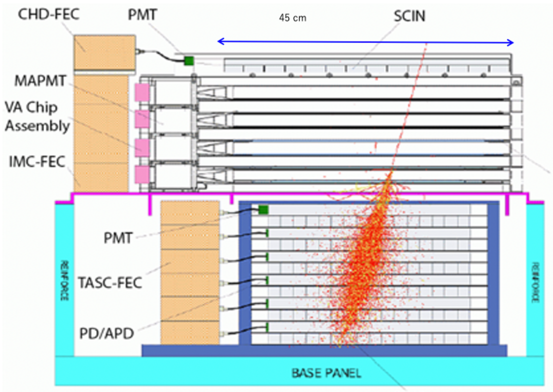

Figure 1: Schematic view of CALET, and 1 TeV simulated electron event is overwritten.

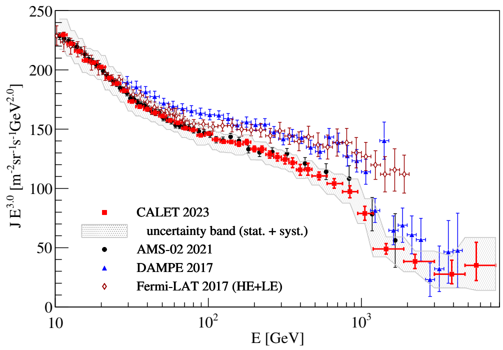

Figure 2: All-electron spectrum measured by CALET [5], where the gray band indicates the quadrature sum of statistical and systematic errors. Also plotted are direct measurements in space [6–8].

70% for electrons. Details of the analysis method and study of the systematic uncertainties are described in Ref. [5]. The latest results of the electron + positron (all-electron) spectrum from CALET [5], based on 2637 days of flight data collected with the HE trigger [9], are shown in Fig. 2. The spectrum integrates 7.02 million electron (+ positron) events above 10.6 GeV and 7.5 TeV. The CALET spectrum shows good agreement with AMS-02 [8] data up to 2 TeV, albeit using different detection techniques.

The flux suppression above 1 TeV, predicted by radiative cooling during propagation in the Galaxy [10, 11], is clearly observed by CALET and is consistent with DAMPE data [7] within errors. The significance of a broken power-law or exponentially cutoff power-law fit exceeds 6.5σ when compared to a single power-law fit with an index of -3.18 ± 0.01 [5].

9 electron candidates above 4.8 TeV have been observed, consistent with an estimation of electron flux from a nearby source based on an interpretation model [12] using DRAGON [13]. Further observations are required to draw a definitive conclusion.

3.2 Proton and Nuclei spectra

CALET is capable of measuring proton and nuclei spectra with single-element charge resolution. In Fig. 3, the latest proton [14] and helium [15] spectra measured by CALET as a function of rigidity are shown, based on 2757 and 2392 days of operation, respectively. The contribution of ^{3}He to the flux is accounted for by assuming the same ^{3}He/^{4}He ratio as measured by AMS-02 [16], and the ratio is extrapolated to higher energies using a single power-law fit. The CALET results are consistent with measurements from magnetic spectrometers [8, 17] up to their maximum detectable rigidity ($\sim$2 TeV). Both spectra exhibit clear hardening around 500 GV and softening around 10 TV, indicating the necessity for new models of cosmic ray acceleration or propagation mechanisms.

The spectra of boron, carbon, and oxygen from 8.4 GeV/n to 3.8 TeV/n are presented in Fig. 4, based on 2554 days of operation, which provides higher statistics than those reported in Refs. [19, 20]. The analysis methodology employed is consistent with that described in Ref. [20], and the latest findings are fully in agreement with our previously published data. The boron and carbon spectra are scaled by factors of 5 and 1.1, respectively, to facilitate overlap with the low-energy region of the oxygen spectrum. The total background contamination in the boron sample is approximately 1% for $E_{\mathrm{TASC}} < 100$ GeV, increasing logarithmically with E_{TASC} above this threshold, reaching around 7% at 1.5 TeV. For carbon and oxygen, the back-

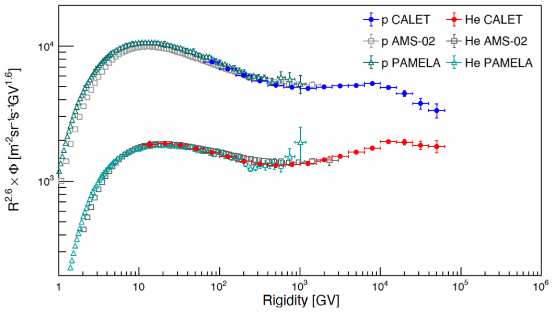

Figure 3: Proton and helium spectra with CALET as a function of rigidity [14,15], together with previous observations [8,17]. Only statistical errors are shown

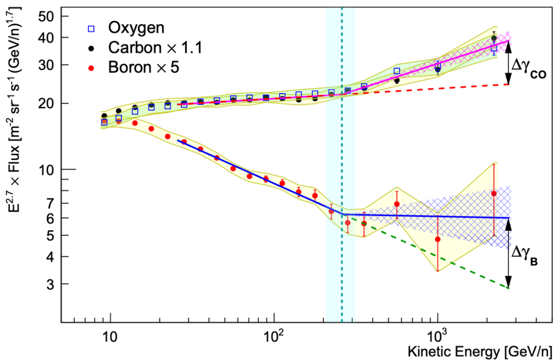

Figure 4: Boron, carbon and oxygen spectra fitted with the DPL functions [18].

ground contamination remains below 1%. The isotopic composition of boron is assumed to be $^{11}\mathrm{B}/(^{10}\mathrm{B}+^{11}\mathrm{B}) = 0.7$ for all energies. The energy spectra exhibit clear differences, consistent with the expectations for primary and secondary cosmic rays. The fitting results suggest, albeit with low statistical significance, that the flux for boron hardens more than that for carbon and oxygen above 200 GeV/n. A simultaneous double power law (DPL) fit to the carbon and oxygen spectra in the energy range from 25 to 3800 GeV/n yields $\gamma_{CO} = -2.66 \pm 0.02$, $\Delta\gamma_{CO} = 0.19 \pm 0.04$ and $E_0 = 260 \pm 50$ GeV/n, confirming our initial results reported in Ref. [19]. Fitting the boron flux with a fixed E_0 results in $\gamma_B = -3.03 \pm 0.03$, $\Delta\gamma_B = 0.32 \pm 0.14$.

A similar indication is derived from the simultaneous fit to the B/C and B/O flux ratios, as illustrated in Fig. 5. Fitting single power law functions (SPLs) to the B/C and B/O ratios in the energy range from 25 GeV/n to 3800 GeV/n yields a mean spectral index of $\Gamma = 0.376 \pm 0.014$ (χ/d.o.f.= 19/27). However, a DPL function provides a better fit, suggesting a trend towards a flattening of the B/C and B/O ratios at high energies, with a spectral index change of $\Delta\Gamma = -0.22 \pm 0.10$ (χ^2/d.o.f.= 15/26) above E_0, which remains fixed in the fit. For the Leaky Box Model fit [21], including a residual material around supernova remnants of approximately 1 g/cm^2 yields a better fit compared to the model with zero residual material, as shown in Fig. 5 [18].

CALET will explore the periodic table in the multi-TeV range with excellent charge identification for individual elements. The preliminary spectra of heavy nuclei (C, O, Ne, Mg, Si, S, Ca, and Fe) up to 100 TeV, as a function of kinetic energy per particle, are shown in Fig. 6. The error bars represent statistical uncertainties only.

4 Summary and future prospects

During its first 8.5 years of operation aboard the ISS, CALET gathered new data on cosmic-ray spectra, including those of all-electrons, protons, helium, and heavy nuclei. Additionally, CALET provided data on the abundance ratios of ultra-heavy cosmic-ray nuclei [22], gamma-ray measurements [23], GRB observations, and searches for gravitational wave event counterparts [24]. The charge-dependent solar modulation was clearly observed during the descending phase of solar cycle 24, with observations continuing into cycle 25 [25]. CALET's operation has been extended to 2030 with approval from JAXA, ASI, and NASA. Improved statistics and refined analyses with additional data collected during the mission will allow for extended measurements to higher energies and enhanced spectral analyses, contributing to a deeper understanding of cosmic-ray phenomena.

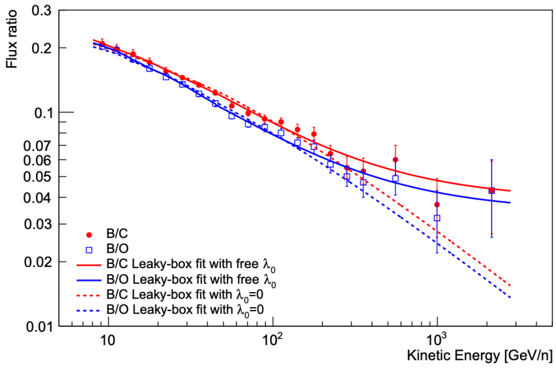

Figure 5: Simultaneous fit of the CALET B/C and B/O flux ratios with a leaky-box model leaving the λ_0 parameter free to vary (solid line) or fixing it at zero (dashed line), respectively [18]. The error bars are the quadratic sum of the statistical and systematic uncertainties.

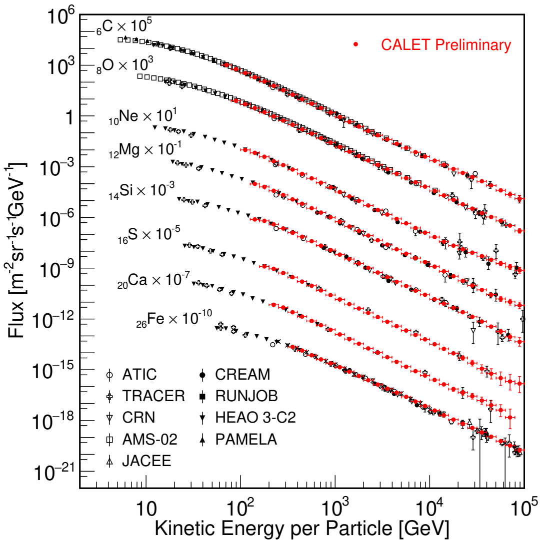

Figure 6: Preliminary results of major heavy spectra with CALET up to 100 TeV.

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