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Galactic cosmic ray spectral measurements with the DAMPE space mission

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on behalf of the DAMPE collaboration

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Abstract. The space-based DAMPE (DArk Matter Particle Explorer) detector has been taking data since its successful launch in December 2015. Its main scientific goals include the indirect search for dark matter signatures in the cosmic electron and gamma-ray spectra, the measurements of galactic cosmic ray fluxes from tens of GeV up to hundreds of TeV and high energy gamma ray astronomy above a few GeV. In particular, results on proton and helium, which revealed new spectral features, will be described. Ongoing analyses on light, medium, and heavy mass nuclei will be outlined, together with results on secondary-to-primary flux ratios.

1 Introduction

DAMPE is a space-based satellite launched in December 2015. Since its launch, it is operating in a sun-synchronous orbit at an altitude of about 500 km. The DAMPE payload was designed to achieve several scientific objectives: the main ones include the indirect search for dark matter, looking for possible hints in gamma-ray and electron-positron spectra, the monitoring and survey of gamma-ray sky and transient objects and the detection of galactic cosmic rays (CRs), in the energy range from a few tens of GeV up to hundreds of TeV for the most abundant nuclei [1].

The design of the experiment includes four sub-detectors to properly reconstruct incoming particle events. A schematic view of the detector is shown in fig.1. Starting from the top, the first is the Plastic Scintillator Detector (PSD) [2], which consists of two orthogonal planes with a double layer configuration of scintillator strips. It is used to measure the absolute value of the charge and to act as an anti-coincidence detector for γ-rays identification. Then, a Silicon-Tungsten traKer-converter (STK) [3], composed of 6 X-Y layers of silicon-strip detectors, interleaved with 3 tungsten plates (for photon conversion). This subdetector mainly serves to reconstruct the direction of the charged particles and to provide additional charge measurements. The bismuth germanium oxide (BGO) calorimeter consists of BGO scintillation crystals arranged in 14 layers in a hodoscopic configuration. Its high segmentation enables a detailed reconstruction of the shower topology [4]. Thus, it provides a measurement of the energy of the event as well as discrimination between electromagnetic and hadronic showers. On the bottom, a NeUtron Detector (NUD) used to further improve

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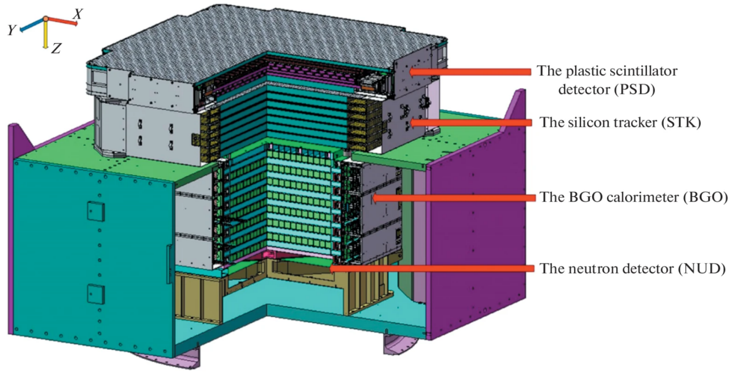


Figure 1. Schematic view of the DAMPE detector.

the lepton/hadron identification capability: it consists of one layer of four boron-loaded scintillator tiles [5].

Between 2014 and 2015, several beam test campaigns were conducted at CERN to validate the detector's performance and establish calibration parameters [7–9]. These tests employed various particle beams, including electrons, photons, pions, protons, and nuclear fragments. Following the DAMPE launch, during the first two weeks a dedicated calibration using cosmic rays was performed. The results were compared with the CERN beam test data to confirm the detector's on-orbit performance. Moreover, periodic calibrations are carried out during on-orbit operations to monitor energy and charge measurements, the detector stability and to ensure detection efficiency [6].

During its years of operation, DAMPE has performed smoothly, with an average daily acquisition rate of 5.2 million events. Furthermore, since its launch the DAMPE collaboration has obtained numerous results relevant to its physics goals. This document focuses on DAMPE's measurements of galactic cosmic rays, outlining the detector's performance and the current state of research in the field.

2 Measurements of galactic cosmic rays

2.1 The all-electron (e^+ e^-) spectrum

With 530 days of data DAMPE performed the measurement of the all-electron spectrum between 25 GeV and 4.6 TeV. The DAMPE spectrum, shown in fig.2, exhibits a hardening at ∼ 50 GeV in agreement with FERMI-LAT and AMS-02 and the first direct observation of a spectral break at an energy of ∼0.9 TeV, previously suggested by HESS. The major challenge of this analysis was rejecting the background mainly represented by protons. Thus, the e^-e^+ sample was selected with high purity thanks to the efficient electromagnetic/hadronic shower discrimination provided by the BGO calorimeter

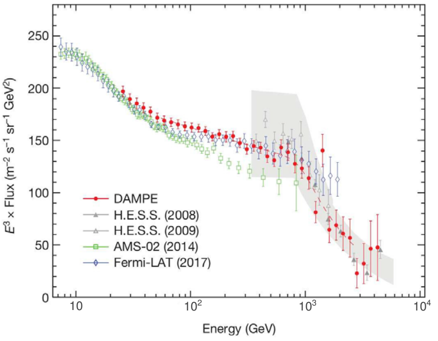


Figure 2. DAMPE all-electron spectrum with error bars including systematic and statistical uncertainties [10] and a smoothly broken power law fit (red dashed line). The spectrum is in comparison with measurements from AMS-02, Fermi-LAT and HESS (the grey band represents its systematic error) [11].

with a discrimination factor of 10^5-10^6, obtaining a proton rejection efficiency of 99.99% and an electron selection efficiency of 90%. The measurement of the all-electron spectrum is of significant interest because it provides a probe for the study of local astrophysical sources and it could enable the indirect dark matter observation. In fact, currently, there are ongoing analyses with the aim of updating the spectrum using a larger sample and implementing machine learning algorithms to further improve the background rejection and extend the measurement beyond 10 TeV [12, 13].

2.2 Proton and helium spectra

DAMPE measured the individual spectra of protons in 2019 and helium in 2021, shown in fig.3. The proton spectrum has been measured in the 40 GeV - 100 TeV energy range, using 2.5 years of data. It presents a hardening at about ~500 GeV, confirming previous observations by other experiments, and also the first evidence of a softening at ~14 TeV, with a significance of 4.7σ and a change in the spectral index of $\Delta\gamma = +0.25 \pm 0.07$ [14].

The DAMPE helium spectrum has been measured between 70 GeV and 80 TeV with 4.5 years of data, and similarly to protons, it is characterised by a hardening followed by a softening. The hardening is observed at ~1.3 TeV, confirming previous measurements reported by other experiments; while the softening has been revealed with a significance of 4.2σ at ~34 TeV and a change of slope of $\Delta\gamma = 0.51^{+0.18}_{-0.20}$ [16].

The collaboration is currently working to update the proton and helium spectra by integrating new statistics collected in the last years and by employing machine learning methods to enhance the performance of particle tracking and identification [20].

Identifying and precisely measuring the hardening and softening features in nuclei spectra are crucial for obtaining insights into the mechanisms driving CR acceleration and propagation within the galaxy. In this context, fig.4 presents the preliminary spectra as a function of kinetic energy per nucleon (left) and rigidity (right), with green dashed lines to indicate the spectral break positions. The better alignment in the right plots implies that both, hardening and softening, are more likely due to rigidity-dependent mechanisms.

Moreover, DAMPE determined the combined p+He flux using an independent analysis based on the selection of a combined sample of protons and helium together, allowing for less stringent selection criteria because of reduced cross-contamination issues. As a result,

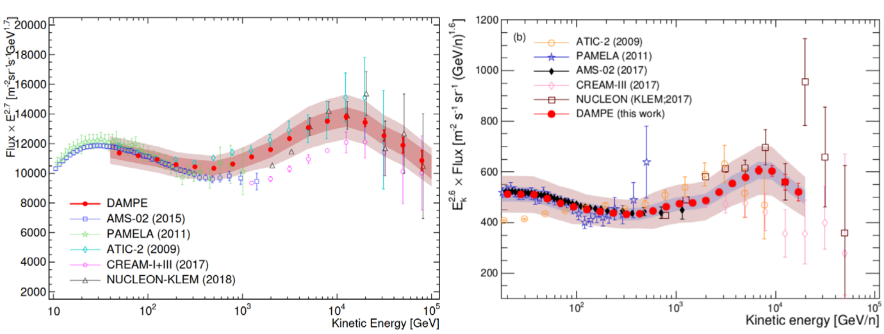


Figure 3. DAMPE proton (left) and He (right) individual spectra compared with measurements from other experiments, [15, 17].with red error bars for the statistical uncertainties, the inner band to indicate the estimated systematic uncertainties and the outer band to the total systematic uncertainties including those from the hadronic models [14, 16].

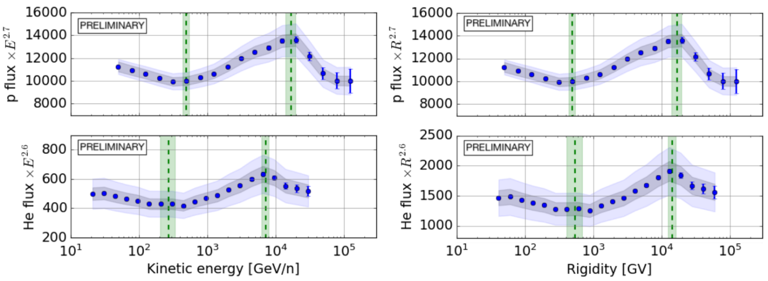


Figure 4. Updated preliminary DAMPE fluxes for protons (top) and helium nuclei (bottom) are shown as functions of kinetic energy per nucleon (left) and rigidity (right). Vertical dashed lines indicate the most probable break positions [20].

the analysis achieved larger statistics and extended to higher energies with respect to the studies that focus on the individual element spectra. The spectrum, measured from 46 GeV to 464 TeV, confirmed the hardening and the softening features, at ∼ 600 GeV and ∼29 TeV respectively, and gave a hint of a second spectral hardening at ∼150 TeV.

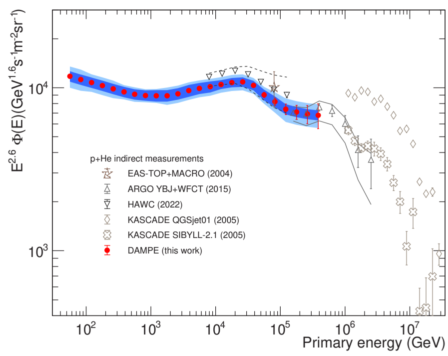


Figure 5. DAMPE p + He spectrum (red dots) [18] compared with indirect measurements from other experiments [19].

2.3 Flux ratios

In 2022 DAMPE measured the secondary-to-primary flux ratios B/C and B/O, as shown in fig. 6, which are of significant importance to probe the CR diffusion mechanisms [22]. Both ratios exhibit a hardening at ∼100 GeV/n with high significance, 5.6 σ and 6.9σ respectively.

Also secondary-to-secondary flux ratios provide insights into cosmic ray propagation and their interaction with interstellar matter. Currently, there are ongoing analyses on Li/B and

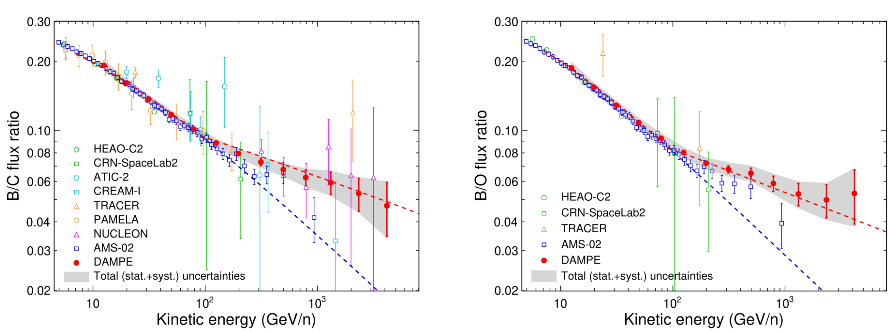
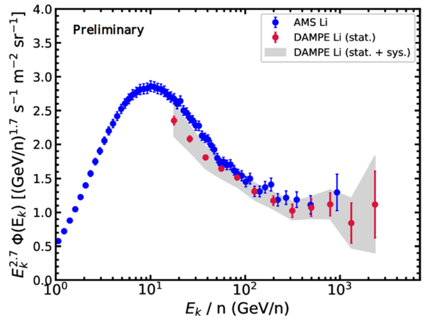


Figure 6. DAMPE secondary-to-primary flux ratios as function of the kinetic energy per nucleon: boron-to-carbon (left) and boron-to-oxygen (right) [22], in comparison with other experiments results [23].

Be/B flux ratios which are focusing on reducing background contamination and evaluating the systematic uncertainties [24].

2.4 Secondary cosmic rays spectra

Ongoing measurements are focusing on the individual spectra of secondary CRs, such as lithium, beryllium and boron [24]. Preliminary results are shown in fig.7 based on 6 years of data. These spectra also exhibit a hardening at a few hundred GeV/n, confirming results previously reported by other experiments.



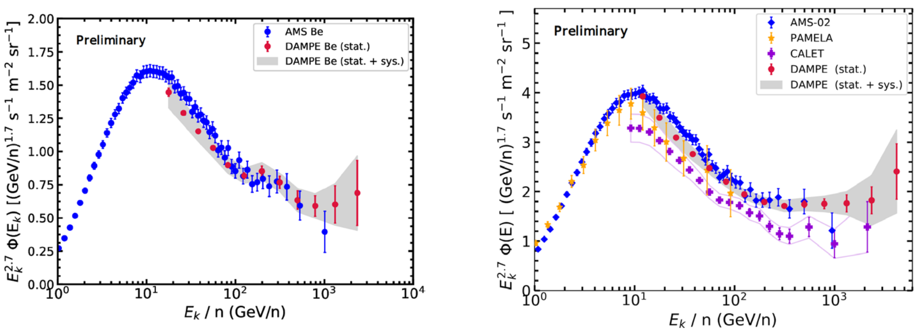


Figure 7. DAMPE preliminary spectra of secondary cosmic ray lithium (top), beryllium (bottom left) and boron (bottom right), compared with measurements from other experiments [25].

2.5 Heavier nuclei spectra

Several analyses that involve medium and heavy mass nuclei are in progress. Using 8 years of data, recent preliminary measurements have determined the fluxes of carbon, oxygen (see fig.8) and combined CNO group (see left side of fig.9). Similarly to the analyses on light mass nuclei, the individual C and O spectra are characterised by a hardening feature at a few hundred GeV/n. Additionally, the combined CNO spectrum confirms this trend, displaying a spectral break around ~8 TeV.

Considering the previously discussed findings on CR nuclei, it is particularly interesting to examine the spectral properties of heavier nuclei and possibly determine whether the hardening and the softening depend on the rigidity or kinetic energy per nucleon. Moreover, these elements also offer an opportunity for investigating fragmentation processes. However, measurements of heavy nuclei encounter challenges related to particle charge identification, are affected by the relatively high fragmentation cross-sections and by the contamination from other elements. Current investigations focus on elements such as neon, magnesium, silicon and iron, as well as heavier nuclei beyond Fe. For example, the right plot of fig.9 shows the preliminary DAMPE iron spectrum, derived from 8 years of flight data. At present, the collaboration is working to finalise these measurements by optimising the particle selection strategy through innovative machine learning techniques.

2.6 The all-particle spectrum

A preliminary analysis for the all-particle spectrum is being carried out using with a loose event selection compared to the spectral studies of individual nuclei. The selection criteria

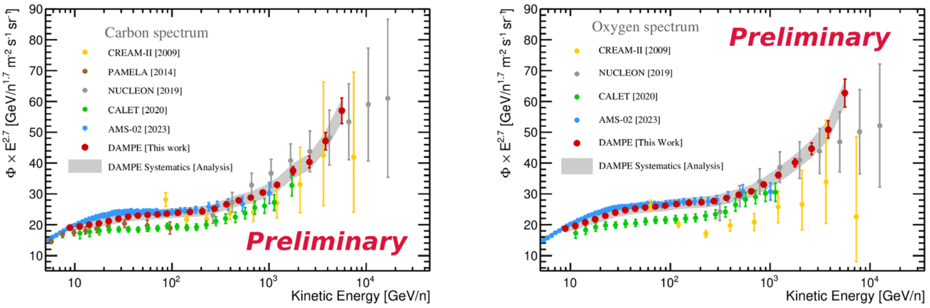


Figure 8. Preliminary DAMPE carbon (left), oxygen (right) spectra in comparison with results from other experiments [27].

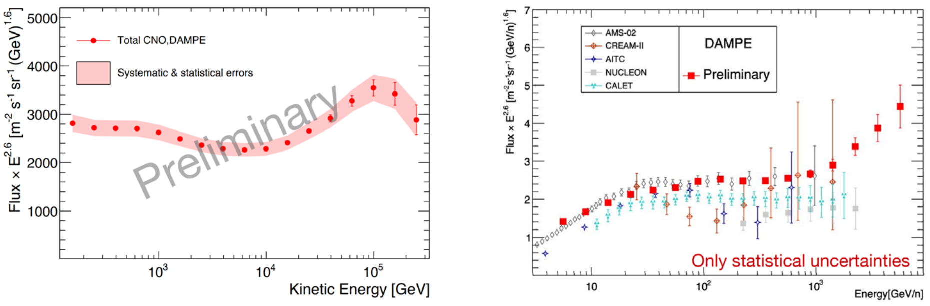


Figure 9. Preliminary DAMPE combined carbon-nitrogen-oxygen (left) and iron (right) spectra performed using 8 years of data. The iron spectrum has error bars including only statistical uncertainty and it is compared with other experiments results [28].

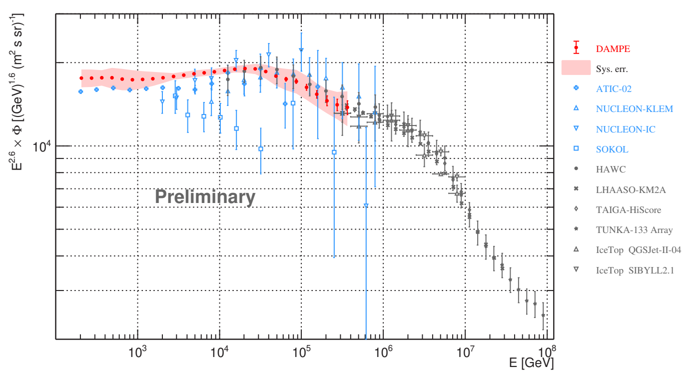


Figure 10. Preliminary DAMPE all-particle spectrum compared with measurements performed by space-based (light-blue markers) and ground-based (gray markers) experiments [29]. The statistical error is represented by error bars; the full evaluation of the systematic uncertainty is ongoing and is represented by the red band.

focus solely on calorimetric variables, without applying cuts for the particles' charge identification. This method enables to have a high statistical sample and pursue the measurement to high energies up to hundreds of TeV, with the potential to reach 1 PeV and have more details about the behavior of the CR flux. The preliminary spectrum is illustrated in fig.10.

2.7 Hadronic cross-section measurements

DAMPE conducted the measurement of the proton and He-4 inelastic hadronic cross sections with a $Bi_4Ge_3O_{12}$ (BGO) target [30]. The analysis is based on 88 months of data and is performed using an unbinned likelihood method. Proton cross-sections were measured in the energy range of 19 GeV to 9 TeV, while helium measurements covered 5 GeV/n to 3 TeV/n, both shown in fig.11. Accurate determination of proton and helium-4 cross-sections is critical for improving CR spectra measurements. In fact, applying the corrections derived from these cross-section measurements reduced discrepancies in the flux normalization of protons and He by 1.1% and 6.4%, respectively. Future perspectives foresee to apply the methodologies developed in this analysis also to other cosmic ray ions, such as carbon and oxygen, which are promising candidates due to their relatively high fluxes.

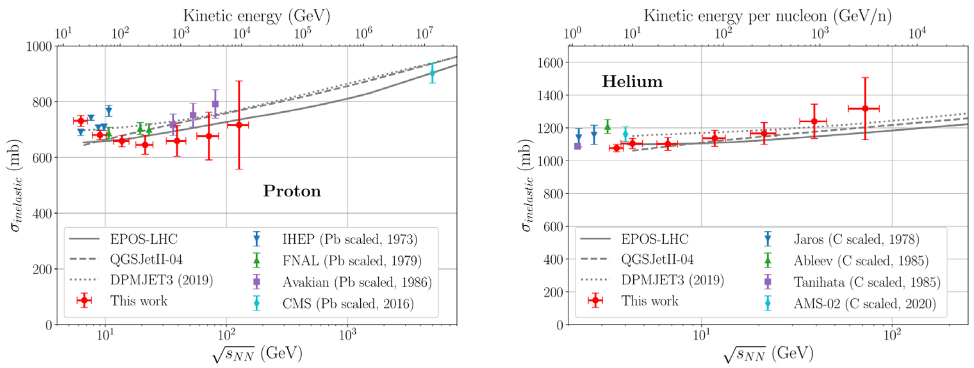


Figure 11. DAMPE inelastic cross section of protons (left) and He-4 (right) nuclei on a $Bi_4Ge_3O_{12}$ target, together with model predictions and similar previous measurements properly scaled for comparison [30].

3 Conclusions

DAMPE is a space-based detector that has been operational since December 2015, continuously collecting data with good performances and obtaining important results. It is contributing in the progress in studying galactic CRs pursuing the research in this field and offering valuable insights into single elements energy spectra. Relevant findings include the measurement of the all-electron spectrum, which revealed a spectral break around 0.9 TeV, as well as the observation of proton and helium spectra, which exhibited a softening feature at rigidities near 15 TV. DAMPE has also measured the B/C and B/O ratios, observing a hardening around 100 GeV/n. Ongoing analyses aim to determine the light, medium, and heavy mass CR spectra and further investigate flux ratios.

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