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Study of the galactic cosmic rays with the DAMPE space mission(*)

I. Cagnoli(1)(2)(**), I. De Mitri(1)(2), P. Savina(1)(2) on behalf of the DAMPE Collaboration

(1) *Gran Sasso Science Institute (GSSI) - Via Iacobucci 2, I-67100 L'Aquila, Italy*
(2) *Istituto Nazionale di Fisica Nucleare (INFN), LNGS - I-67100 Assergi, L'Aquila, Italy*

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Summary. — DAMPE (DArk Matter Particle Explorer) is a space-based experiment, operative since December 2015. Its main scientific objectives include the indirect search for dark matter in the spectra of leptons and gamma rays, the study of primary cosmic rays up to energies of hundreds of TeV, and gamma-ray astronomy. In this contribution the main results obtained so far in the study of the energy spectra of $e^- + e^+$, protons and nuclei are described.

1. – Introduction

The DArk Matter Particle Explorer (DAMPE) is a space-borne particle detector that was launched on December 17, 2015, at an altitude of ∼500 km, in a sun-synchronous orbit. DAMPE aims to cover a broad scientific program, including the study of electrons and photons spectra in the range from few GeV up to TeV, also with the goal to search for possible Dark Matter signatures. Moreover, it aims to perform the measurement of the flux and composition of cosmic-ray (CR) nuclei, up to hundreds of TeV, giving new insight for acceleration and propagation mechanisms.

The instrument consists of a Plastic Scintillator Detector (PSD), a Silicon-Tungsten tracker converter (STK), a BGO calorimeter and a NeUtron Detector (NUD). The PSD [1], composed of 82 modules in a double layer configuration, measures the absolute value of the charge of incident CRs and provides charged-particle background rejection for γ-ray events. The STK [2] is composed of 12 silicon micro-strip detector layers in alternative orthogonal arrangement and 3 thin tungsten layers inserted to promote photon conversion. It provides the particles trajectory reconstruction and an additional information on their charge, while also the reconstruction of the direction of γ-rays converted into e^+ e^- pairs. The BGO calorimeter [3], made of bismuth germanium oxide crystals, has a total depth of ∼32 radiation lengths and ∼1.6 nuclear interaction lengths. It measures the energy of incident particles and provides an efficient discrimination between

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(**) E-mail: `irene.cagnoli@gssi.it`.

electromagnetic and hadronic showers. The NUD [4], made of 4 boron-loaded plastic scintillators, provides a further improvement in the e^-/had separation power. With high energy resolution, strong e^-/had separation power and reasonably large acceptance, DAMPE is expected to detect cosmic electrons and photons in the energy range from ∼10 GeV to ∼10 TeV and measure the fluxes and the mass composition of galactic CR nuclei up to hundreds of TeV.

Since its launch, DAMPE has been regularly collected data, demonstrating extremely smooth performance and leading to several significant measurements. The following section focuses on the main results obtained in the analyses of cosmic ray nuclei.

2. – Measurements of galactic cosmic ray spectra

2.1. *The all-electron (e^++e^-) spectrum.* – In 2017, DAMPE presented an accurate measurement of the e^-+e^+ spectrum between 25 GeV and 4.6 TeV (see fig. 1), enabling the first direct observation of a variation in the spectrum at around 0.9 TeV, based on 530 days of data [5]. To achieve this measurement, excellent electron/proton separation was necessary, as the cosmic ray proton flux is orders of magnitude higher than the e^-+e^+ flux. A powerful discrimination was achieved, mainly thanks to the BGO calorimeter segmentation.

A proton rejection efficiency of 99.99% was achieved, while maintaining an electron/positron efficiency of 90%. The DAMPE e^-+e^+ spectrum is characterized by a hardening at around 50 GeV, in agreement with results from Fermi-LAT and AMS-02. It provides the first direct evidence of a break at 0.9 TeV, confirming with high precision a feature previously hinted at by HESS The best fit for the DAMPE spectrum is obtained using a broken power law model, with the spectral index changing from γ ∼3.1 to γ ∼3.9.

New ongoing analyses aim to extend the measurement to higher energies by increasing the dataset and improving background rejection with the help of Machine Learning algorithms [10,11]. This could be particularly interesting, as hints of a possible contribution

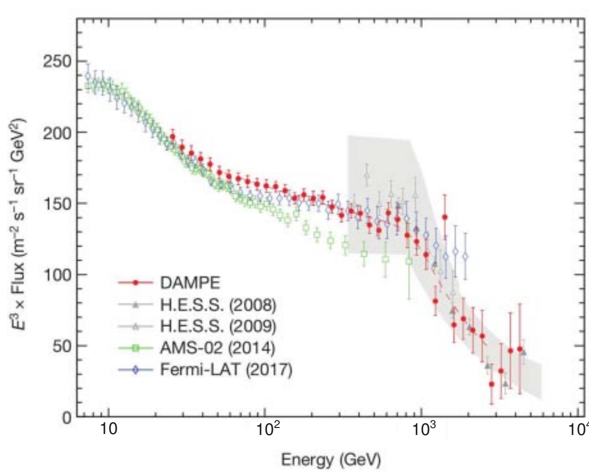

Fig. 1. – DAMPE all-electron spectrum (red markers) and smoothly broken power law fit (red dashed line), compared with measurements from AMS-02 and Fermi-LAT and HESS(the grey band represents its systematic errors apart from the ∼15% energy scale uncertainty). The error bars include both the systematic and the statistical uncertainties [5].

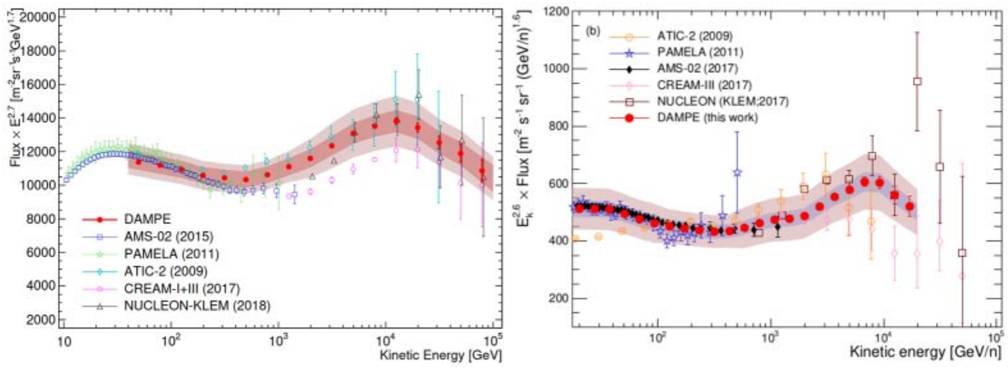

Fig. 2. – DAMPE proton (left) and He (right) individual spectra, compared with results published by other instruments. The red error bars refer to the statistical uncertainties. The inner band shows the estimated systematic uncertainties, the outer band refers to the total systematic uncertainties including also those from the hadronic models [12, 13].

from nearby sources or signatures of dark matter might be detected at higher energies above the TeV range.

2˙2. *Proton and helium spectra.* – The proton spectrum from 40 GeV to 100 TeV was measured (left plot of fig. 2) using data collected from January 2016 to June 2018 (30 months).

Proton candidates are identified based on a cut applied to the PSD charge, which is measured independently by the two PSD layers and then averaged to obtain the final value. This cut is dependent on the energy deposited in the BGO calorimeter. This result confirmed a hardening previously observed by other experiments at hundreds of GeV and revealed a softening around 14 TeV with a significance of 4.7σ [12].

Similarly, the DAMPE helium spectrum was measured (right plot of fig. 2) in the energy range from 70 GeV to 80 TeV of total kinetic energy, based on data collected over 54 months (from January 2016 to June 2020). This result confirmed the hardening observed by other experiments and provided strong evidence for a softening at around 34 TeV with a significance of 4.3σ [13]. Comparing the softening positions of the proton and helium spectra (see fig. 3) suggests that this feature is more likely dependent on

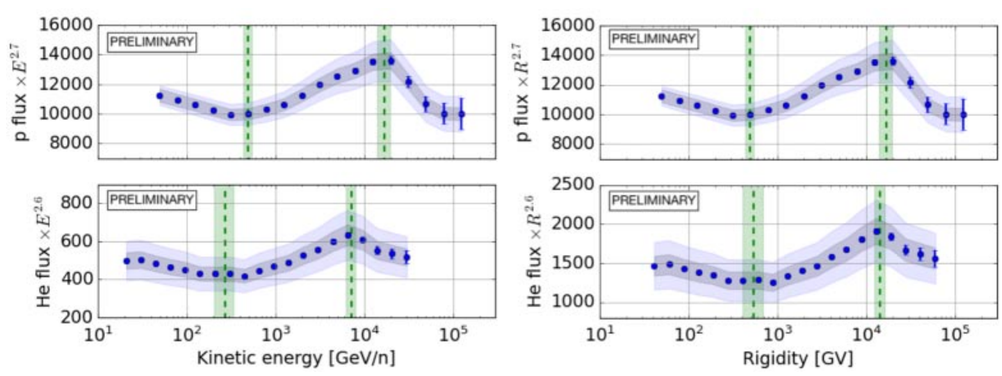

Fig. 3. – From new ongoing analyses, preliminary updated DAMPE proton (top) and helium (bottom) fluxes as function of kinetic energy per nucleon (left) and rigidity (right). The most probable break positions are marked with vertical dashed lines [15].

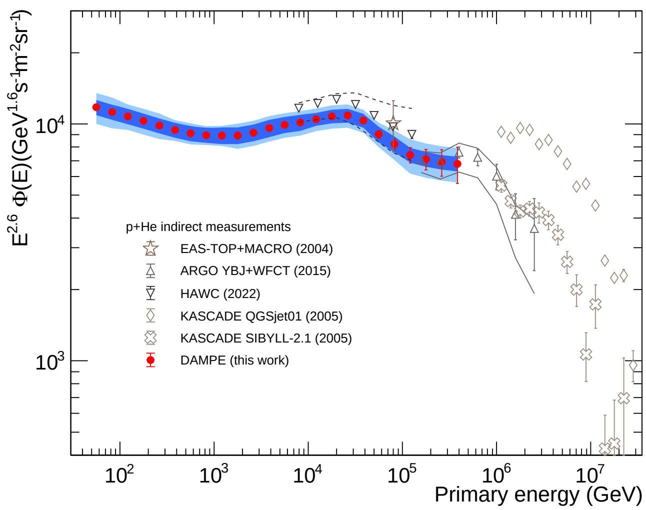

Fig. 4. – DAMPE p + He spectrum (red dots) [14], compared with indirect measurements from other experiments.

rigidity rather than the energy per nucleon, though the other hypothesis cannot be ruled out due to measurement uncertainties [15].

Additionally, the p+He energy spectrum is also being measured, shown in fig. 4. This analysis selects both proton and helium together and is independent from the individual spectra. This allows for the collection of additional statistics, thereby reaching higher energies with low background, due to minimal contamination from other light nuclei (which have much lower fluxes). This result further confirms the hardening and softening features, and by reaching high energies comparable to those measured by indirect experiments, it provides a link between direct and indirect CRs observations [14].

2·3. *Heavier nuclei spectra*. – There are different ongoing analyses that are studying the spectra of heavier nuclei. Recently, the fluxes of boron, carbon, oxygen and combined CNO group have been measured. They are shown in fig. 5.

The analysis of boron is based on 72 months of data [18]. Current efforts focus on estimating systematic errors, with major contributions arising from hadronic modeling and the estimation of residual background in the charge selection procedure.

Preliminary measurements of the cosmic ray carbon and oxygen spectra are presented. These measurements were obtained using classical, well-established methods. Additionally, ongoing efforts are focused on optimizing the particle selection strategy by employing powerful machine learning techniques. These newer methods require further validation through comparison with the classical approaches [16].

Furthermore, a combined measurement of carbon, nitrogen, and oxygen cosmic rays has been conducted. This approach benefits from larger statistics and reduced uncertainty in charge selection.

Similarly to the analyses on the lightest primary cosmic rays, all the spectra exhibit a hardening feature at a few hundred GeV per nucleon. Additionally, the CNO spectrum suggests a possible softening around 100 TeV [19].

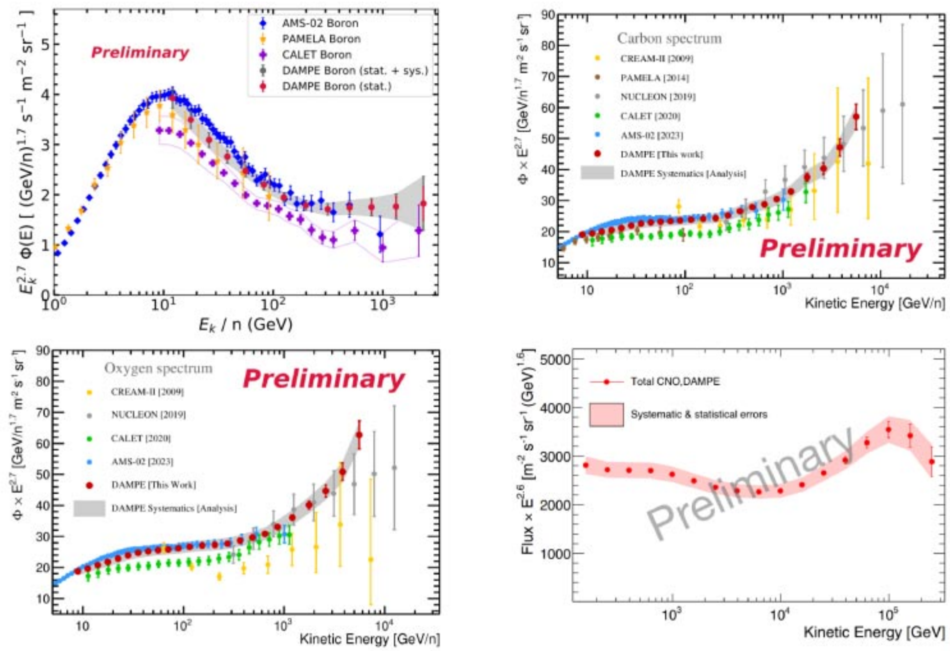

Fig. 5. – Preliminary DAMPE boron (top-left), carbon (top-right), oxygen (bottom-left) spectra as function of kinetic energy per nucleon and combined carbon-nitrogen-oxygen spectrum (bottom-right) as function of kinetic energy [16], compared with measurements published by other instruments.

2·4. *Flux ratios and the all-particle spectrum.* – Additional information on the production and propagation mechanisms of cosmic rays in our galaxy can be obtained from measurements of the abundances of secondary nuclei relative to primary ones. Recently, DAMPE has measured the B/C and B/O flux ratios [17]. Both ratios in fig. 6 ex-

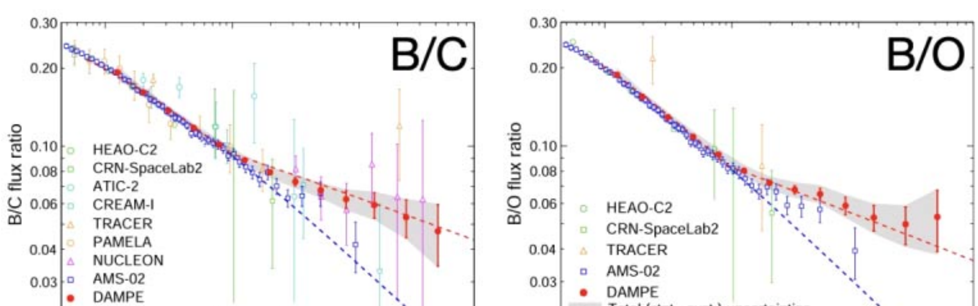

Fig. 6. – DAMPE secondary-to-primary flux ratios as function of kinetic energy per nucleon: boron-to-carbon (left) and boron-to-oxygen (right) [17], compared with results from other experiments. The blue dashed lines represent the fit based on a GALPROP model that assumes a single power-law dependence of the diffusion coefficient on rigidity. In contrast, the red dashed lines depict the results when incorporating a hardening of the diffusion coefficient at 200 GV.

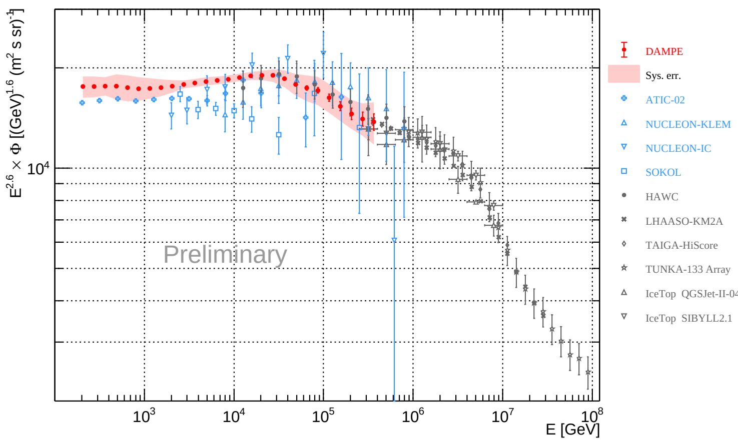

Fig. 7. – Preliminary all-particle spectrum of DAMPE with statistical error bars and a red band for the systematic uncertainty, compared with measurements performed by space-based and ground-based experiments.

hibit a hardening at 100 GeV/n, supporting the hypothesis that this feature is related to propagation effects. Furthermore, preliminary results have been obtained for the ratios between different secondary components, such as Li/B and Be/B [18]. However, the analysis is still ongoing, with particular attention to background reduction and a comprehensive evaluation of systematics.

In the case of the all-particle spectrum, an analysis was conducted with a less stringent event selection compared to spectral analyses of individual nuclei: the selection is based only on calorimetric variables and not on the particles' charge. This approach allowed for performing the measurement up to hundreds TeV with good performance and a large statistical sample, with the potential to extend the measurement up to 1 PeV. The spectrum is shown in fig. 7. There is an indication of a possible structure around tens of TeV, which requires further investigation. The full evaluation of the systematics is still ongoing.

3. – Conclusions

The DAMPE detector's acceptance and performance have enabled significant advancements in the study of Galactic Cosmic Rays. Measurements of the $e^{-}+e^{+}$, proton, and helium spectra have revealed new features with important implications for our understanding of the field. Current studies focus on extending direct measurements to higher energies with high precision, alongside ongoing analyses of light, medium, and heavy cosmic ray species.

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