PROCEEDINGS OF SCIENCE

Measurements of galactic CR energy spectra with the DAMPE space mission

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The DArk Matter Particle Explorer (DAMPE) is a space-based particle detector launched on December 2015 from the Jiuquan Satellite Launch Center in China, and since then smoothly operating in a Sun-synchronous orbit. The main goals of the DAMPE mission include the study of the Cosmic-Ray Electron-positron (CRE) energy spectrum, the study of galactic cosmic-rays (CR), gamma-ray astronomy, and indirect dark matter search. The large acceptance and the detector figures make DAMPE able to measure the CREs and gamma-rays spectra up to few TeV, and cosmic-ray nuclei spectra up to hundreds of TeV, with unprecedented statistics and resolutions. An overview of the DAMPE mission will be presented, along with main results and ongoing activities, focusing on CR spectral measurements.

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[*] Speaker

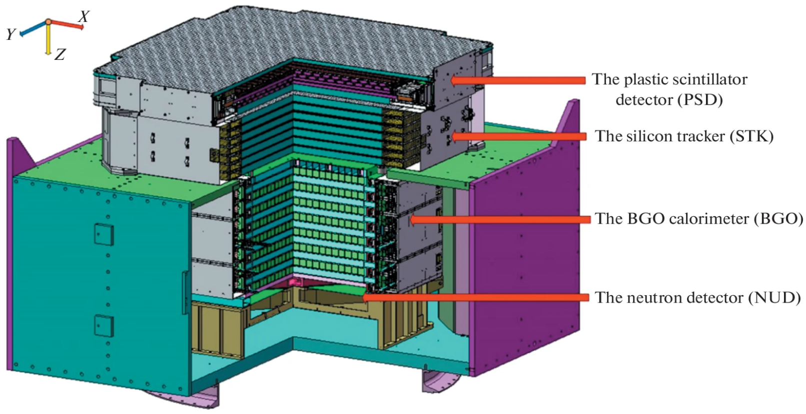


Figure 1: A schematic view of the DAMPE detector [1] .

1. Introduction

The DArk Matter Particle Explorer [1] (DAMPE) is space-based, multiple-purpose particle detector. The payload was launched in December 2015 and it is smoothly operating in a sun-synchronous orbit at an altitude of 500 km. The scientific objectives of the mission are many and include the measurement of high energy galactic cosmic rays (CRs), the search for Dark Matter (DM) signatures in the gamma-ray and electron plus positron spectra and the study of sources in the gamma-ray sky.

2. The detector

DAMPE is made of 4 sub-detectors (see Fig. 1) that perform the tasks of particle identification, tracking and energy measurement of the incoming CRs. Its total weight is 1400 kg and it has a power consumption of 400 W. From the top, the first detector is the Plastic Scintillator Detector (PSD) [2], made of two planes of plastic scintillator bars of $884 \times 28 \times 5$ mm^3 dimensions, staggered to provide better hermeticity. It is used to measure the absolute value of the charge Z of the incoming particles through the energy released in its bars ($\frac{dE}{dx} \propto Z^2$). It also provides gamma-ray identification. The Silicon-Tungsten Tracker (STK) [3] is made of 6 silicon planes, each one including two micro-strip layers segmented along the X and Y directions, interleaved with three tungsten plates that increase the gamma-ray pair-conversion probability. The energy deposited in the silicon layers can also provide additional information on the impinging CR charge. The calorimeter [4] is made of Bismuth Germanium Oxide (BGO) bars, packed in a total of 14 layers and oriented in the X or Y direction, with each layer being orthogonal with respect to the adjacent ones. The full calorimeter is 32 radiation lengths and 1.6 interaction lengths deep. It measures the energy of the incoming particle and discriminates electromagnetic from hadronic showers looking at the topology. Finally the Neutron Detector [5] (NUD), made of one layer of four boron-loaded scintillator tiles, gives additional information to separate hadrons from electrons/positrons by measuring the neutron content of the shower.

These features make DAMPE a powerful and precise CR telescope. The detector acceptance for electrons is 0.3 m^2 sr above 30 GeV with an excellent energy resolution of 1.2% at 100 GeV.

DAMPE is able to measure leptons and gamma-rays in an energy range of 10 GeV - 10 TeV and protons and nuclei from 40 GeV up to 200 TeV with a very large acceptance.

3. Electron-positron spectrum

DAMPE measured the electron-positron spectrum [6] in an energy range from 25 GeV to 4.6 TeV with 530 days of data. Since the CR proton flux is orders of magnitude higher than the electron/positron ones, an excellent electron/proton separation is crucial for this measurement. As previously mentioned DAMPE is able to discriminate between the two thanks to the high segmentation of the BGO calorimeter. Specifically, two variables related to the BGO shower topology are used. The first one $\mathcal{F}_{last}$ is defined as the ratio between the energy deposited in the last BGO layer and the total energy released in the calorimeter. The second one $sumRMS$ describes the shower transverse spread:

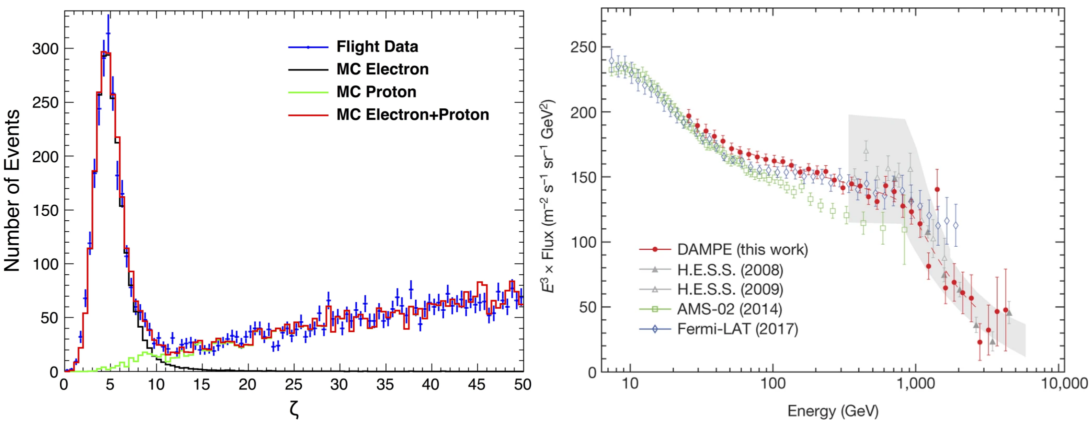
$$sumRMS = \sum_{i=1}^{N_{layers}} RMS_i = \sum_{i=1}^{N_{layers}} \sqrt{\frac{\sum_j (x_{j,i} - x_{c,i})^2 E_{j,i}}{\sum_j E_{j,i}}} \tag{1}$$

where $x_{j,i}$ is the coordinate of the j-th bar of the i-th layer, $x_{c,i}$ the coordinate of the identified shower center in the i-th layer and $E_{j,i}$ the energy deposit in the j-th bar of the i-th layer. The two can also be combined in a single dimensionless variable, ζ:

$$\zeta = \frac{\mathcal{F}_{last} \times (sumRMS/mm)^4}{8 \times 10^6} \tag{2}$$

These variables allow a powerful discrimination: a proton rejection efficiency of 99.99% can be achieved with an electron/positron efficiency as high as 90%.

The DAMPE electron-positron spectrum (see Fig.2) shows a hardening at ~ 50 GeV in agreement with results from FERMI-LAT [7] and AMS-02 [8] and provides the first direct evidence of a



(a) Variable ζ showing electron / proton separation.

(b) DAMPE electron-positron flux.

Figure 2: Distribution of the ζ variable for flight data and MC samples (2a), for events with BGO energy in the 500 GeV - 1 TeV energy range. DAMPE electron-positron flux (2b) [6], plotted with the results from other experiments [7–10]. The gray shaded region represents the systematic uncertainty on the H.E.S.S. measurement.

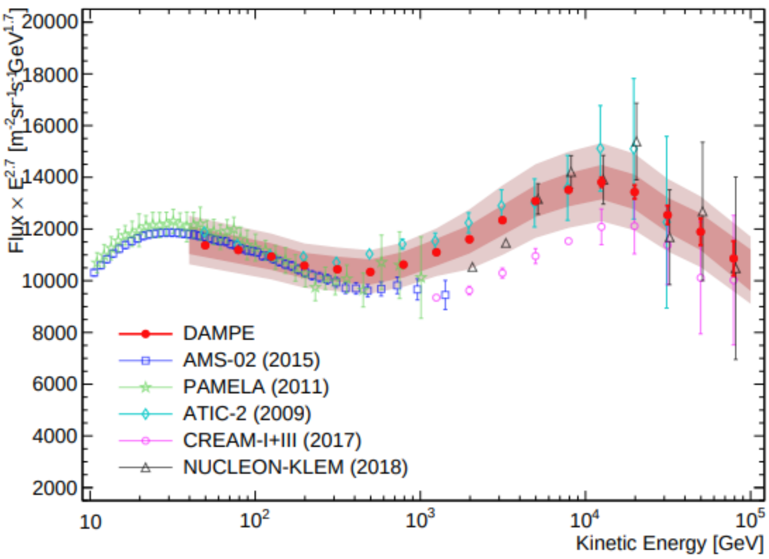


Figure 3: DAMPE proton spectrum [15] showing a softening at ∼ 14 TeV, compared with measurements from various experiments [16–20].

break at 0.9 TeV, confirming with high precision a feature hinted by H.E.S.S. [9, 10]. The spectral index, extracted by fitting a broken power law model to the spectrum, varies from $\gamma \sim 3.1$ to $\gamma \sim 3.9$. This study will be updated with larger statistics as well as the implementation of machine learning algorithms [11] to further improve the background rejection. Extending the measurement to even higher energy could be very interesting for a possible contribution of nearby sources [12–14].

4. Protons and Helium nuclei

The proton spectrum from 40 GeV to 100 TeV [15] has been measured using the data acquired on flight from January 2016 to June 2018 (30 months), and shown in fig. 3. This result confirmed a hardening previously observed by other experiments at hundreds of GeV [16–20], and also showed a softening at ∼ 14 TeV with 4.7 σ significance. The presence of these breaks in the spectrum pointed out that a single power law spectrum is not adequate for the description of experimental data.

An analogous behaviour has been observed for helium: the DAMPE helium spectrum was measured in the energy range from 70 GeV up to 80 TeV of total kinetic energy [21], and obtained using 54 months of data (from January 2016 to June 2020), as shown in fig. 4. This spectrum confirmed the hardening also observed by other experiments [17–19, 22, 23], showing a strong evidence for a softening at ∼ 34 TeV with 4.3 σ significance. The position of the softening, when compared to the proton spectrum one, suggests that this feature is more likely to be dependent on rigidity rather than the energy per nucleon, even though other scenarios cannot be excluded due to measurement uncertainties.

The p+He energy spectrum is also being measured [24], giving the possibility of reaching the highest energies ever detected with direct techniques, potentially extending up to hundreds of TeV.

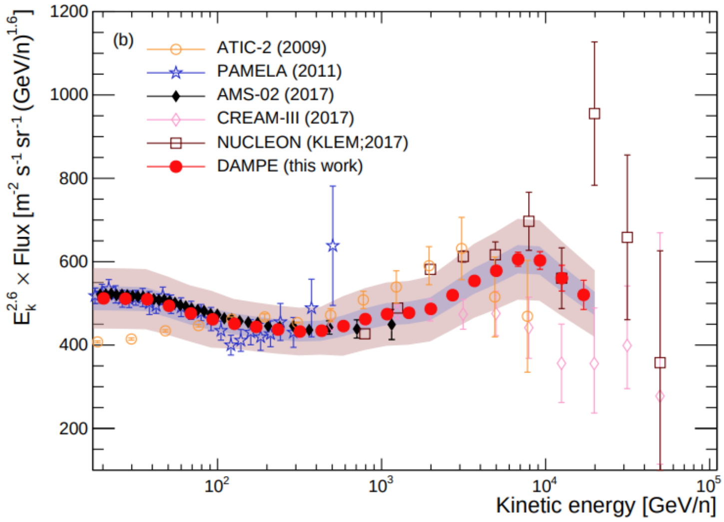


Figure 4: DAMPE Helium spectrum [21] showing a break at ~ 34 TeV, compared with measurements from various experiments [17–19, 22, 23].

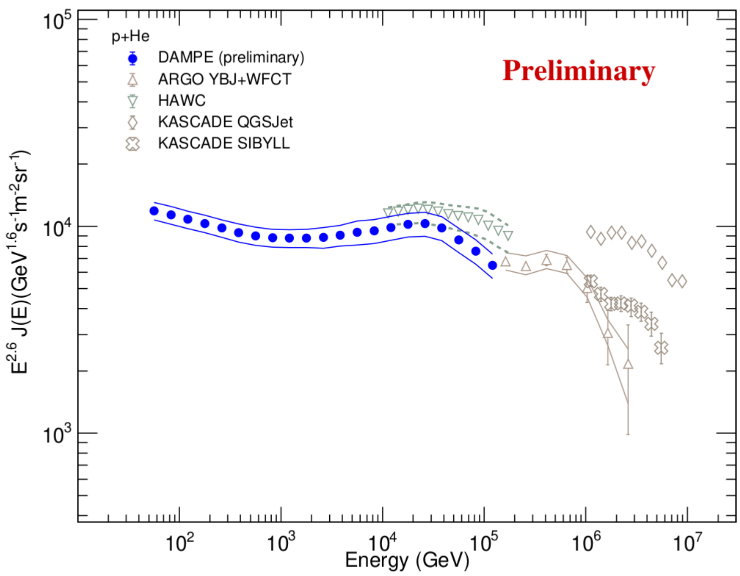


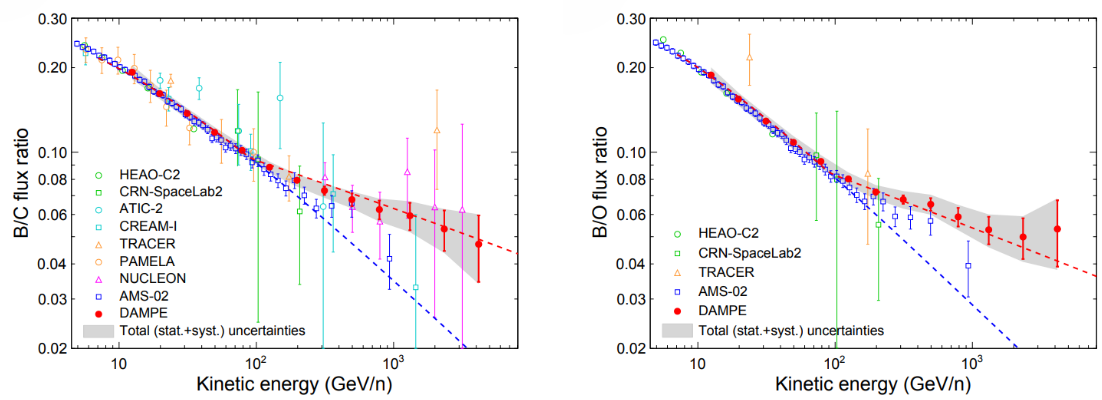
Figure 5: DAMPE preliminary results of p+He spectrum [24], compared with HAWC, ARGO-YBJ and KASCADE [25–27].

This analysis features very high statistical sample with negligible contamination, since the flux of the other light nuclei is much lower. The high-energy part of the spectrum can also be compared with indirect measurements. Preliminary results are shown in fig. 5. The result obtained from this measurement can also be important in order to have a comparison between direct and indirect techniques, potentially providing a better understanding of the uncertainties on interaction models in Extensive Air Showers simulations.

5. Heavier Nuclei

Several analyses on heavier nuclei are currently ongoing. Among these, the Boron to Carbon and Boron to Oxygen flux ratios have been recently measured [28] from 10 GeV/n to 5.6 TeV/n with 6 years of data. A hardening of both ratios has been observed at ~ 100 GeV/n for the first time, giving important input to acceleration and propagation models. These flux ratios are shown in fig. 6a and 6b, compared to results from previous experiments [29–32].

The spectra of several nuclear species are currently being studied from Lithium up to Iron, with some examples shown in [33] and [34].



(a) Boron over Carbon flux ratio **(b)** Boron over Oxygen flux ratio

Figure 6: DAMPE Boron over Carbon (a) and Boron over Oxygen (b) flux ratios [28], compared with measurements from various experiments [29][30][31][32]. A hardening is clearly observed at ~ 100 GeV/n

6. Conclusions

DAMPE is a space-based cosmic ray detector launched in December 2015. Thanks to its design and stable performance it is providing important contributions to the study of galactic cosmic rays. The electron-positron spectrum, measured between 25 GeV and 4.6 TeV, showed the first direct evidence of a break at the TeV scale. The proton and helium spectra, reaching energies around 100 TeV, revealed a softening at ~ 14 and 34 TeV respectively. A preliminary p+He spectrum, potentially reaching energies higher than the single element ones, highlights the possibility of an interesting comparison with results from ground based experiments. Recently published measurements of B/C and B/O flux ratios from 10 GeV/n to 5.6 TeV/n exhibit a hardening at ~ 100 GeV/n with novel implications on the propagation of cosmic rays in our galaxy. The analysis of single energy spectra for several other nuclei is currently ongoing.

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