PROCEEDINGS OF SCIENCE

Measurement of the cosmic p+He energy spectrum with the DAMPE space mission

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It is currently well established that proton and helium constitute the main component of cosmic radiation in the energy range from tens of GeV to hundreds of TeV. Their direct detection and separation have been carried out in the past years using several space-based instruments and long-flying balloons, while ground-based experiments provided results at high energies but with large systematics due to the limited mass resolution. Surprisingly, two structures were found in the direct measurements of individual proton and helium spectra which deviates from the single power law model, proposed by standard acceleration and propagation mechanisms. Moreover, results from ground-based experiments opened the scenario of a light component (i.e. p+He) knee in the cosmic ray spectrum, even with large uncertainties. The p+He direct measurement, using looser selection cuts compared to individual p and He analyses, besides giving a valuable cross-check, can enlarge the event statistics and then extend the energy range to larger values, covering an overlap region between direct and indirect measurements, and exploring it for the first time with high precision. Among the space-based cosmic ray detectors in operation at present, the DArk Matter Particle Explorer (DAMPE) has the capability of providing results on p+He up to the highest energies, thanks to its large acceptance and deep calorimeter. In this work, the p+He spectrum measured up to 300 TeV, using 6 years of data collected with the DAMPE satellite, will be presented.

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1. Introduction

In recent years, various experiments provided interesting results regarding Galactic Cosmic-Ray (GCR) physics. Experimental findings have revealed deviations in CR nuclei spectra from the expected power law predicted by conventional acceleration mechanisms [1] manifested in a *hardening* of the spectrum at hundreds of GeV [2–18], followed by a *softening* above 10 TeV [17–19]. Current-generation space-borne detectors can provide precise CR measurements, that allow us to further explore the aforementioned features and eventually clarify GCR acceleration and propagation mechanisms. Specifically, the DAMPE (DArk Matter Particle Explorer) space mission, launched in December 2015, was designed to study GCRs up to hundreds of TeV, e^- + e^+ and gamma rays up to ~10 TeV, and to search for indirect signatures of dark matter. This detector provided insightful results regarding CR physics [16–18]. The DAMPE instrument comprises four sub-detectors, namely: a plastic scintillator detector (PSD) for electron-gamma ray discrimination and charge measurement, a silicon-tungsten tracker-converter (STK) for charged particle direction measurement and photon conversion, a bismuth germanium oxide (BGO) imaging calorimeter, with a total depth of more than 31 radiation lengths and ~1.6 nuclear interaction lengths, which measures particle energy and distinguishes between hadronic and electromagnetic showers, and a neutron detector (NUD) that collects neutrons from hadronic showers for improved event identification. DAMPE's deep calorimeter, large acceptance, and good energy resolution make it ideal for measuring cosmic rays up to a few hundred TeV [20]. In this study, the high energy spectrum for p+He particles up to 300 TeV measured using six years of flight data acquired by DAMPE is presented. By using a combined sample of protons and helium nuclei, the event selection criteria can be relaxed compared to individual proton or helium samples, ensuring minimal contamination and yielding increased statistics. As a result, the additional statistics enable an extension of the energy range up to ~300 TeV, establishing a connection between space-based and ground-based measurements, and exploring this energy region from space for the first time with relatively small uncertainties. More details on this analysis and a deeper discussion can be found in [21].

2. Monte Carlo simulations

Monte Carlo (MC) simulations are essential to interpret the detector response to different particles. In this work, the GEANT4 version 4.10.5 toolkit [22] and the FTFP_BERT physics list* are used to simulate protons (10 GeV - 100 TeV) and helium nuclei (10 GeV - 500 TeV). For higher energy ranges, namely 100 TeV - 1 PeV for protons and 500 TeV - 1 PeV for helium, the EPOS-LHC physics list [23] is used. Prior to the space deployment of DAMPE, beam tests at CERN were conducted [24–26], demonstrating a fair agreement between the measured data and simulations. To assess the systematic uncertainty arising from hadronic interaction models, additional MC data are generated using alternative models. Specifically, FLUKA 2011.2x [27] with the DPMJET3 model [28–30] is used for helium nuclei, while GEANT4-QGSP_BERT is employed for protons. Comparing the spectra computed from these two MC samples provides an estimate for the systematic uncertainty related to the hadronic interaction model.

*https://geant4.web.cern.ch/node/302

3. Event selection and effective acceptance

In this analysis, data from 72 months of DAMPE operation (from January 2016 to December 2021) are used, with the exclusion of events occurring within the South Atlantic Anomaly (SAA) region. After accounting for instrumental dead time, on-orbit calibration time, a period affected by a significant solar flare between September 9 and September 13, 2017[†], and the time spent in the SAA passage [31], a total live time of around $\sim 14.5\times 10^7$ s remains, which corresponds to approximately 76% of the total operation time. Both the flight data and Monte Carlo (MC) simulations undergo an initial event preselection, followed by the selection of proton and helium.

(i) Preselection - The preselection consists of the following criteria:

- Events capable of initiating a shower at the top of the calorimeter are selected by requiring the high energy trigger (HET) activation[‡].
- A threshold on the deposited energy in the calorimeter is set at 20 GeV to mitigate the influence of the geomagnetic rigidity cutoff [33].
- To discard most events entering from the sides of the calorimeter, the energy deposited in any single layer of the BGO calorimeter must be lower than 35% of the total energy.
- A well-contained lateral shower spread within the calorimeter is ensured by requiring the shower axis to fall within a central region covering 93% of the calorimeter width. Additionally, events with the maximum energy deposition occurring at the lateral edges of the calorimeter are rejected.

(ii) Track selection - The incoming particle's track is reconstructed using the STK [34], and the highest quality events are selected by combining the STK information with measurements from other sub-detectors. To ensure accurate selection, consistency between the STK track and the signal in the PSD is required, along with a match between the reconstructed track in the STK and the shower axis in the BGO calorimeter.

(iii) Charge selection - CR nuclei are selected based on the energy deposit in the PSD, which is proportional to Z^2 according to the Bethe-Bloch equation (where Z is the charge of the incident particle). Since the energy loss depends on both the particle's charge and its primary energy, the charge selection is performed in different energy bins. Figure 1 illustrates the PSD charge distributions for three energy bins and their comparison with MC data. The PSD energy distributions in each bin are fitted using a Landau convoluted with a Gaussian function (LanGaus), yielding the most probable value (MPV), the Landau width, and the Gaussian sigma. To model the dependence of MPV and sigma values on the total energy deposited in the calorimeter, a fourth-order polynomial function of the logarithm of the energy is used to fit the obtained values. This allows for the determination of charge selection conditions (represented in Figure 1 by vertical dashed lines) with a maximum value of $\mathrm{MPV_{He}} + 6\sigma_{\mathrm{He}}$ and a minimum value of $\mathrm{MPV_p} - 2\sigma_{\mathrm{p}}$ (with $\sigma = \sqrt{Width^2_{\mathrm{Landau}} + \sigma^2_{\mathrm{Gaus}}}$). These limits are optimized to maximize statistics while maintaining a low background level ($\lesssim 0.4\%$ up to 10 TeV).

[†] https://solarflare.njit.edu/datasources.html

[‡] The HET condition corresponds to an energy deposition exceeding around 10 MIPs in the first three BGO layers and over 2 MIPs in the fourth layer [32]

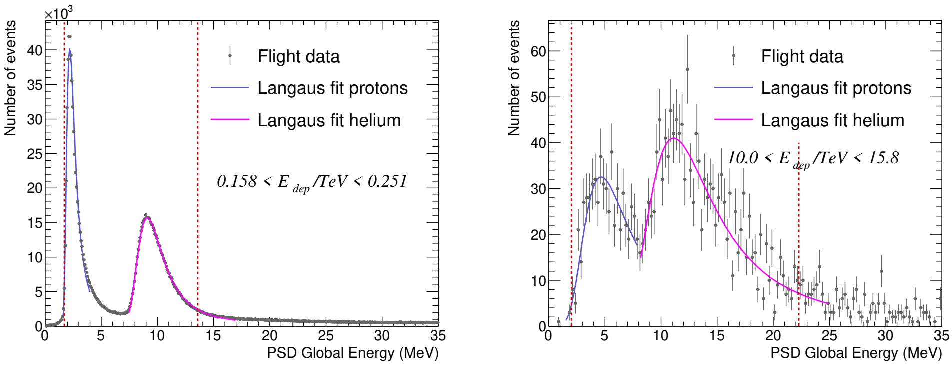

Figure 1: Distributions of PSD global energy (mean value of the energy released in the two DAMPE PSD layers), for events with deposited energy in the BGO calorimeter within 158-251 GeV (left) and 10.0–15.8 TeV (right). Grey points indicate flight data, while the blue and magenta lines represent the LanGaus fit used to retrieve the charge selection condition. The red vertical dashed lines show the charge selection ranges for p+He. The contamination from Lithium and heavier nuclei is negligible in the p+He analysis.

After applying the described selection cuts, the effective acceptance A^{i} (shown in Figure 2, left) is evaluated using the following formula:

$$A^{\mathrm{i}}(E_{\mathrm{T}}^{\mathrm{i}}) = G \times \frac{N(E_{\mathrm{T}}^{\mathrm{i}}, \mathrm{sel})}{N(E_{\mathrm{T}}^{\mathrm{i}})}. \tag{1}$$

G is the geometrical factor used to generate MC data, $N(E_{\mathrm{T}}^{\mathrm{i}})$ indicates the number of MC generated events in the i-th bin of primary energy (E_{T}), and $N(E_{\mathrm{T}}^{\mathrm{i}}, \mathrm{sel})$ represents the number of MC events that pass the selection cuts.

4. Energy measurement and p+He flux

For proton and helium, approximately 35% to 45% of the total energy is contained in the DAMPE calorimeter. Consequently, an unfolding procedure (as described in [35]) is adopted to determine the energy spectrum of the incoming particles. The actual number of events in the i-th bin of true energy, $N(E_{\mathrm{T}}^{\mathrm{i}})$, can be obtained using the following expression:

$$N(E_{\mathrm{T}}^{\mathrm{i}}) = \sum_{j=1}^{n} P\left(E_{\mathrm{T}}^{\mathrm{i}} | E_{\mathrm{O}}^{\mathrm{j}}\right) N(E_{\mathrm{O}}^{\mathrm{j}}), \tag{2}$$

with $P\left(E_{\mathrm{T}}^{\mathrm{i}} | E_{\mathrm{O}}^{\mathrm{j}}\right)$ the response matrix derived from MC simulations (see Figure 2, right) and $N(E_{\mathrm{O}}^{\mathrm{j}})$ the number of observed events in the j-th bin of energy deposited in the calorimeter ($E_{\mathrm{O}}^{\mathrm{j}}$). After the unfolding, the p+He flux can be obtained. In general, the flux for each energy bin, Φ_{i}, can be expressed as:

$$\Phi_{\mathrm{i}} = \frac{\Delta N_{\mathrm{i}}}{\Delta T \times A_{\mathrm{i}} \times \Delta E_{\mathrm{i}}}, \tag{3}$$

where N_{i} is the number of events in the i-th energy bin after the unfolding, ΔT the total live time, A_{i} the acceptance in the i-th bin, and ΔE_{i} the width of the i-th energy interval. The p+He flux

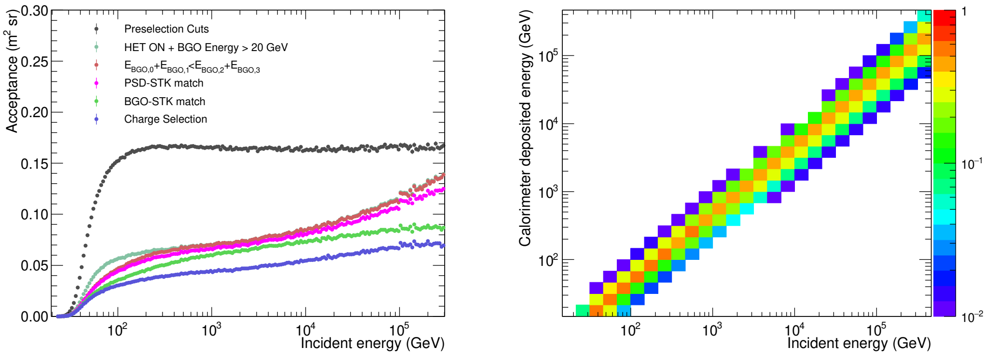

Figure 2: Acceptance for various progressive selection cuts (left) and response matrix (right, [21]) derived from MC simulations of proton and helium. The colors in the matrix represent the probability for an event in an incident energy bin to migrate to different deposited energy bins.

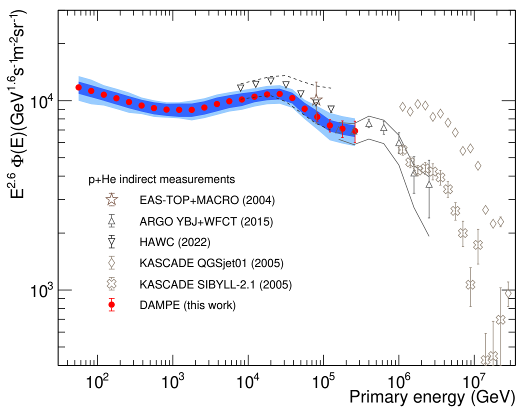

Figure 3: p+He spectrum measured with DAMPE (red circles) compared with indirect p+He measurements from ARGO-YBJ+WFCT [36], HAWC [37], KASCADE [38] and EAS-TOP+MACRO [39] (see also [21]).

is presented in figure 3 in the energy range from 46 GeV to 316 TeV, compared to indirect p+He measurements. The error bars represent the 1σ statistical uncertainties. The continuous bands indicate the systematic uncertainties related to the analysis procedure (inner band) and the overall systematic uncertainties (outer band), including the uncertainties of the hadronic interaction model which represent the most significant contributor, accounting for approximately 10-15%. Other sources of uncertainties, associated with the analysis procedure, are the differences between MC and satellite data when calculating the efficiencies of various selection cuts. Additionally, variations in the MC proton and helium mixtures are considered, affecting the spectrum by a few percent and included within the inner systematic band. The high energy region (approximately from 7 TeV to 130 TeV) of the proton+helium spectrum has been fitted using a smoothly-broken power-law (SBPL) function[§]. The fit indicates the presence of a spectral softening at $28.8^{+6.2}_{-4.4}$ TeV with a significance of 6.6σ and confirms the previous DAMPE results in both proton and helium spectra [17, 18].

[§] a similar approach was adopted in previous studies such as [17, 18, 40, 41]

Moreover, the result from this work is consistent with indirect measurements, although further observations from future space-borne experiments (e.g., HERD [42, 43]) and a spectral extension at higher energies are required to provide further insights. Notably, the p+He spectrum provides a new indication of a potential second hardening around 150 TeV, supported by preliminary findings from the HAWC collaboration [44], and giving hints to the existence of PeVatrons [45].

5. Summary

The DAMPE p+He spectral measurement, in the energy range from 46 GeV to 316 TeV, was presented in this work. This analysis confirms the presence of a spectral softening, with the unprecedented significance of 6.6σ. Considering the combined contribution of proton and helium instead of analyzing them individually, results in additional statistics, allowing the exploration of higher energies while minimizing background effects. Consequently, these findings establish a connection between direct and indirect cosmic-ray measurements, demonstrating a good overall agreement and providing the hint for a new hardening at ~150 TeV.

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