Measurement of cosmic lithium, beryllium and boron with the DAMPE space mission

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Summary. — This work presents the preliminary spectral measurements of secondary cosmic nuclei lithium, beryllium and boron and their ratios to primary fluxes with DAMPE data. The measurement of secondary cosmic rays is fundamental to improve our understanding of their acceleration and propagation mechanisms. The preliminary DAMPE boron flux has been measured from 10 GeV/n to 3.2 TeV/n, featuring a hardening at a few hundreds GeV/n. The preliminary DAMPE Li/C and Be/C ratios are also shown from 14.7 GeV/n to 3.2 TeV/n.

1. – Introduction

Galactic Cosmic Rays (CR) are high-energy particles that are accelerated and travel through our Galaxy, carrying information regarding their sources and the Interstellar Medium (ISM). Specifically, cosmic lithium, beryllium and boron are mainly produced by spallation of heavier nuclei with the ISM and are therefore called secondary cosmic rays. Their stellar nucleosynthesis production abundances are orders of magnitude lower than protons, helium, carbon and oxygen, which are referred to as primary cosmic rays. The AMS-02 experiment has measured lithium, beryllium and boron fluxes [1, 2] in the

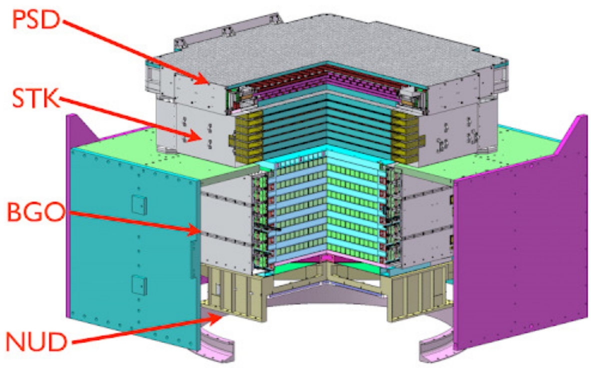


Fig. 1.: Schematic view of the DAMPE detector [5].

1.9 GV - 3.3 TV rigidity range, showing a hardening of the spectral index above 200 GV. The DAMPE experiment recently measured the secondary over primary ratios B/C and B/O [3], fundamental to probe the CR diffusion mechanisms, reporting a hardening at 100 GeV/n in both ratios with high significance, strongly reinforcing the hypothesis of such feature being a propagation related effect. In 2022, the CALET collaboration published the measurement of the boron flux from 8.4 GeV/n to 3.8 TeV/n showing a hardening at energy $E_B \sim 200$ GeV/n [4]; however with the currently available statistics a single power law behavior cannot be excluded with the data collected by the detector. Precision measurements of the secondary cosmic rays are of great importance, allowing the investigation of this feature to gain a better understanding of CR propagation. This work will show preliminary measurements of cosmic lithium, beryllium and boron with data from the DAMPE detector.

2. – The DAMPE detector

The Dark Matter Particle Explorer (DAMPE) is a space-based CR detector, smoothly operating in orbit around the Earth at a 500 km altitude since its launch in December 2015. The instrument (see fig. 1) includes three main sub-detectors: a plastic scintillator (PSD), designed to measure the absolute value of the charge of the incoming particles and identify gamma-rays; a silicon-tungsten tracker-converter (STK) to measure the particles direction while also providing additional information on their charge; a very deep (32 X_O) bismuth germanium oxide electromagnetic calorimeter (BGO) to measure the energy of the particles and to distinguish hadronic and electromagnetic showers. For a full description of the instrumental apparatus, see ref. [5]. To properly measure secondary lithium, beryllium and boron it is fundamental to reject the huge background coming from proton and helium nuclei and select the nucleus of interest. This is achieved

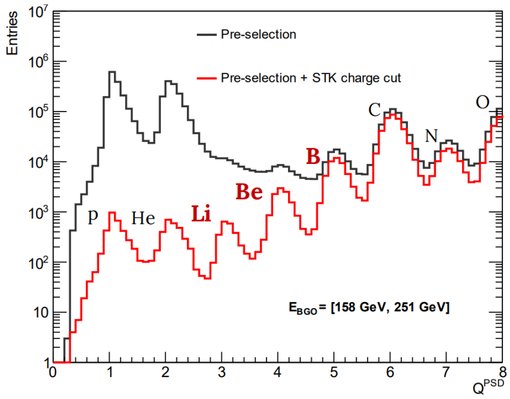


Fig. 2.: PSD-estimated charge in the deposited energy bin $E_{BGO} = [158, 251]$ GeV. The black histogram shows the distribution of the variable after the pre-selection; the red one instead shows the distribution after the STK charge cut has been performed, removing most of the proton and helium events.

combining information from the PSD and the STK.

3. – Event selection

The analysis is based on six years of data collected by DAMPE from 2016 to 2021. To perform the analysis, extensive Monte-Carlo (MC) simulations are produced with the GEANT4 4.10.5 toolkit adopting the FTFP_BERT and EPOS-LHC physics lists for simulations of the three nuclei in the 10 GeV - 500 TeV energy range. Different isotopes are simulated: Li6, Li7, Be7, Be9, Be10, B10 and B11. A weight is then assigned to the simulation samples, corresponding to specific isotopic fractions. The following have been chosen as benchmark fractions: Li6 : Li7 = 1:1, Be7 : Be9 = 1:1 and B10 : B11 = 3:7. As a first selection step, events collected when the satellite crosses the South Atlantic Anomaly are removed. A pre-selection follows with general criteria, selecting properly reconstructed events with a high quality track in the STK and good shower containment in the BGO calorimeter. A lower threshold of 80 (60) GeV on the deposited energy in the BGO is set for the Be, B (Li) analysis, to avoid the geomagnetic rigidity cutoff effect. The nuclei of interest are selected according to the signal in the PSD [6]. The detector consists of four sub-layers, two oriented in the Y and two in the X direction. Due to this configuration, every incoming particle can deposit energy in a different set of sub-layers according to its incoming direction and instrumental effects. At pre-selection stage events are required to have a signal in at least one PSD X and one PSD Y layer. A PSD estimator of the particle charge is defined as:

$$Q^{PSD} = \frac{\sum_i Q_i^{PSD}}{N_{\text{lay}}} \tag{1}$$

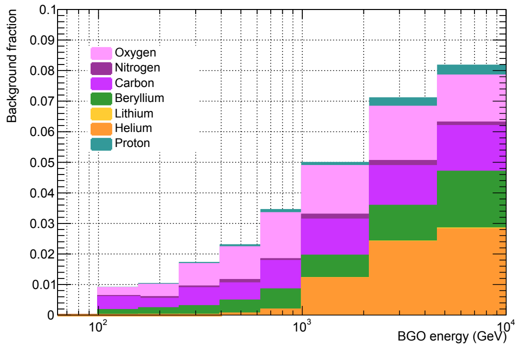


Fig. 3.: Estimated background for the boron analysis in different E_{BG0} bins. The different colors represent the contribution of each nuclei, according to the legend.

where the index i goes over the PSD sub-layers with non-zero signal, checking that charges in successive sub-layers satisfy the condition:

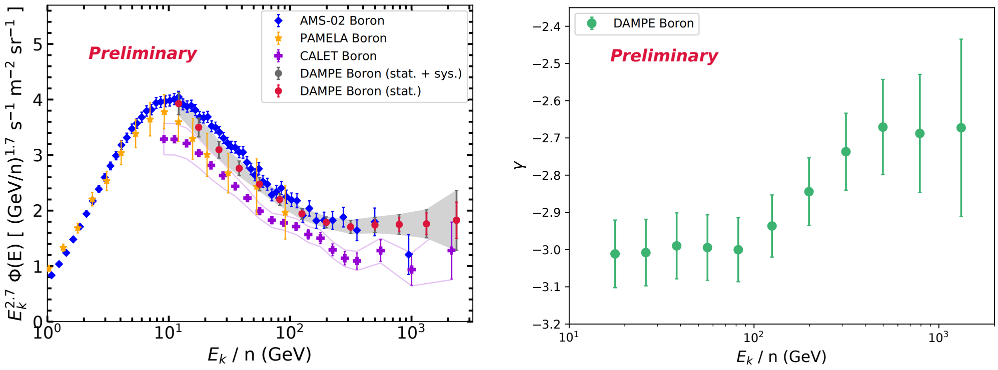
$$|Q_i^{PSD} - Q_{i+1}^{PSD}| < Q_{th} \tag{2}$$

with a $Q_{th} = 1$ threshold choice for Be, B while a more stringent request of $Q_{th} = 0.3$ is adopted for Li. N_{lay} is the number of sub-layers passing this request. The PSD charge is defined in this way to improve the charge resolution by rejecting most events in which the incoming particle undergoes an inelastic interaction inside the PSD. An additional cut on the charge estimated with the first layer of the STK is needed to reject background from proton and helium: a lower threshold of 600 (400) ADC is set for the Be, B (Li) analysis (see fig. 2). The Q_{PSD} peak of the nucleus of interest is fit with a convolution of a Landau and a Gaussian distribution for different E_{BGO} bins, from which the Most Probable Value (MPV) and the width σ are extracted. The dependence of MPV and σ on E_{BGO} are modeled with log-polynomial functions $f_{MPV}(E_{BGO})$ and $f_\sigma(E_{BGO})$ used to define an energy-dependent PSD charge selection window. The selected signal region is:

$$f_{MPV} - n_\sigma^{low} \cdot f_\sigma < Q^{PSD} < f_{MPV} - n_\sigma^{hi} \cdot f_\sigma \tag{3}$$

The Q^{PSD} signal window is chosen as a balance between high statistics and low background contamination. Each nucleus will have its specific functions f_{MPV} and f_σ. The chosen signal windows are $(n_\sigma^{low}, n_\sigma^{hi}) = (1, 2), (1.5, 3), (2, 2.5)$ for Li, Be and B respectively.

Once the PSD charge window is defined, the sample selection is complete. The fraction of background events entering the signal region is evaluated with a MC-based template fit on the Q_{PSD} variable in different E_{BGO} bins. For boron the estimated background



(a) (b)

Fig. 4.: Fig. 4a shows the preliminary boron spectrum measured with the DAMPE detector (red points) compared to PAMELA [7], AMS-02 [2] and CALET results [4]. The gray band shows the sum in quadrature of statistical and systematic uncertainties; the systematic uncertainty related to the choice of hadronic model is not yet included and is under evaluation. Estimated spectral indexes from the sliding window power law fit are shown in Fig. 4b. The chosen window is three point wide.

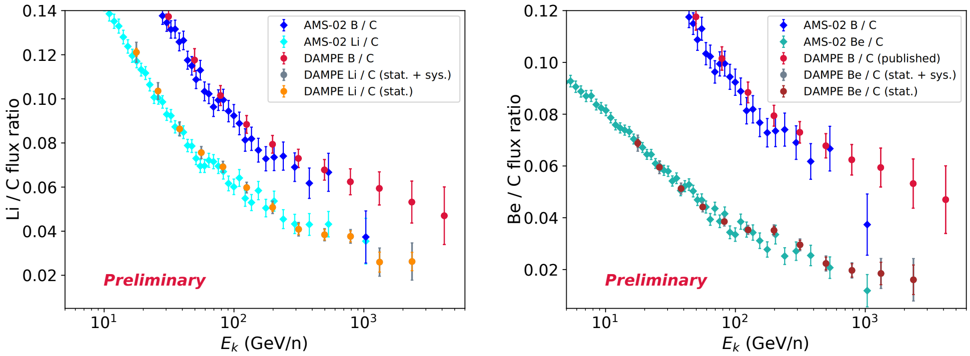
fraction of events inside the signal region is shown in fig. 3: it is below 10% across the whole energy range. For lithium and beryllium instead the background reaches larger percentages, up to 40-60% at the highest energies: background subtraction is performed.

4. – Results

The differential spectrum of cosmic ray species is measured as a function of kinetic energy per nucleon according to:

$$\Phi_i = \frac{N_i}{\Delta T \cdot A_i \cdot \Delta E_i} \qquad (4)$$

where N_i is the number of events in the signal sample after unfolding [8] of the observed data; ΔT is the livetime corresponding to the data sample, A_i is the MC-estimated acceptance, based on GEANT4 simulations, and ΔE_i is the energy bin width. The preliminary DAMPE boron spectrum was measured from 10 GeV/n to 3.2 TeV/n and is shown in fig. 4a. The largest contributions to the total uncertainty come from the statistical uncertainty and the systematic uncertainty related to the background. A single power law model was fit to three point windows across the spectrum, extracting the power law index γ, shown in fig. 4b. The spectral index goes from $\gamma \sim -3.0$ to $\gamma \sim -2.7$, highlighting the hardening in the region of few hundreds GeV/n. The DAMPE boron spectrum is in agreement within uncertainties with the AMS-02 measurement, extending



(a) (b)

Fig. 5.: Preliminary Li/C (fig. 5a) and Be/C (fig. 5b) ratios measured with DAMPE data, compared to AMS-02 measurements [2].

to higher energies. The CALET spectrum has a similar shape but different normalization.

The secondary over primary ratios Li/C and Be/C have been measured with DAMPE data from 14.7 GeV/n to 3.2 TeV/n, shown in fig. 5. The DAMPE measurements are in good agreement with AMS-02 measurements. The largest contributions to the total uncertainty come form the background subtraction, the assumed isotopic composition and the validation of the MC-estimated acceptance.

5. – Conclusions

This work has presented preliminary results regarding the measurement of secondary cosmic rays with DAMPE data. Specifically the cosmic ray boron spectrum was measured from 10 GeV/n to 3.2 TeV/n featuring a hardening at a few hundreds GeV/n. The preliminary Li/C and Be/C ratios have been measured from 14.7 GeV/n to 3.2 TeV/n and are in good agreement with AMS-02 data. The goals for the final analysis are the extension of measurements to higher energy and a complete evaluation of the uncertainty, aiming at a further reduction of the background as well.

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