

Energy spectra and flux ratios of BCNO cosmic-ray nuclei measured by CALET up to multi-TeV energies

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We present the measurement of the individual energy spectra for boron, carbon, nitrogen and oxygen cosmic rays based on data collected by the CALorimetric Electron Telescope (CALET) during 10 years of operation on the International Space Station (ISS). These spectra are measured in the energy range from 10 GeV/n to several TeV/n using a fully calorimetric instrument, 1.3 nuclear interaction lengths thick, equipped with charge detectors providing single element resolution. The B, C and O spectra have been updated from our previously published results with more statistics and refined systematic uncertainty estimates, while the N energy spectrum is a new preliminary measurement. We also present the energy dependence of the B/C, B/O and N/O flux ratios, interpreting these results with fitting models including a spectral break in the power law of the diffusion coefficient and a constant residual propagation path length. Finally, we show the combined CNO flux up to hundreds of TeV in particle energy.

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1. Introduction

Over the past decade, direct measurements of cosmic rays (CRs) have revealed unexpected spectral features that significantly deviate from the simple power-law behaviour predicted by traditional models. In particular, spectral hardening has been observed in multiple nuclear species at energies of a few hundred GeV/ n , with the spectral index change being more pronounced for secondary CR than for primaries [1–5]. These findings have led to the development of various theoretical models to explain the observed phenomena, invoking revised acceleration mechanisms [6, 7], energy-dependent diffusion [10–12], reacceleration processes [13] and the possible contribution of local sources [8, 9] and source grammage within the acceleration region [14–16]. Furthermore, the spectrum of protons and helium nuclei has recently been observed to soften around 10 TeV/ n , suggesting that similar behaviour may occur in heavier nuclei as well. To fully understand these effects and disentangle the contributions of source and propagation mechanisms, it is crucial to extend CR measurements in the multi-TeV region with high-statistics data for individual elements. In this paper we present new direct measurements of the energy spectra of carbon and oxygen in the energy range from 8.4 GeV/ n to 18.9 TeV/ n , and of boron and nitrogen up to 6.7 TeV/ n , based on the data collected by CALET [17] from Oct. 13, 2015 to Dec. 31, 2024 aboard the ISS.

2. Detector

The CALET instrument consists of three main components: a CHarge Detector (CHD), a finely segmented pre-shower IMaging Calorimeter (IMC), and a Total AbSorption Calorimeter (TASC). The IMC is composed of 7 tungsten plates interleaved with 8 double layers of scintillating fibers, oriented alternately along orthogonal directions. These fiber signals are used to reconstruct the arrival direction of cosmic rays with an angular resolution of $\sim 0.1^\circ$ and a spatial resolution of the impact point on the CHD of $\sim 220 \mu\text{m}$ [18]. Positioned above the IMC, the CHD comprises two orthogonal hodoscopes, each made up of 14 plastic scintillator paddles. Particle identification is based on charge reconstruction from the energy deposits measured in each CHD layer (Z_{CHDX} , Z_{CHDY}) and the average energy loss per unit length (dE/dx) along the upper IMC layers (Z_{IMC}) [5]. The CHD is capable of resolving individual elements with atomic numbers from $Z = 1$ to 40, while IMC measurement is limited to $Z \lesssim 14$ due to scintillating fiber saturation. The charge resolution is approximately $0.15 e$ for CHD and $0.24 e$ for IMC, in the elemental range from B to O.

The TASC is built with 12 layers of lead-tungstate (PWO) bars, each read out by photosensors and front-end electronics, providing a dynamic range greater than 10^6 . The total thickness of the CALET instrument corresponds to 30 radiation lengths and 1.3 proton nuclear interaction lengths. A comprehensive calibration campaign was conducted at CERN SPS facility using protons, electrons, and ion fragments [19]. Detailed Monte Carlo (MC) simulations of the detector are carried out using the EPICS package [20], and independent simulations based on Geant4 [21] and FLUKA [22] are used to evaluate systematic uncertainties.

3. Data analysis

We analyzed flight data (FD) collected over 3367 days of CALET operations aboard the ISS. The data were corrected for non-uniform light output, time- and temperature-dependent effects, and gain variations across channels. B, C, N and O candidates are identified from events triggered by the high-energy (HE) shower trigger, which requires coincident signals from the last two IMC

layers and the top TASC layer. The total live time for HE triggers is $T = 6.7 \times 10^4$ hours (86% of the observation time). Event selection requires the events to pass through the entire detector, from the top of the CHD to the bottom of the TASC, and to stay within a fiducial volume, corresponding to a geometric factor of $S\Omega \sim 510 \text{ cm}^2\text{sr}$. Topological cuts are applied to reject misreconstructed events, and charge window cuts ($0.45 e$) are used to isolate the charge peaks in the Z_{CHD} and Z_{IMC} distributions. Additional selection criteria based on Z_{CHD} and Z_{IMC} charge consistency and "track width" helps to reject particles that had undergone charge-changing nuclear interactions. $\sim 8\%$ of the selected events are rejected because their reconstructed trajectories points towards obstructions (i.e. ISS solar panels, robotic arms) blocking the field of view at angles $> 45^\circ$ [23].

With this selection procedure about 3.1×10^5 B, 1.5×10^6 C, 5.4×10^5 N and 2.7×10^6 O nuclei are identified. The energy spectrum for each nuclear species is calculated using the equation:

$$\Phi(E) = \frac{N(E)}{\Delta E \varepsilon(E) S\Omega T} \quad (1)$$

where $N(E)$ represents the number of nuclei detected within the energy bin ΔE centered at E , which is the primary particle's kinetic energy per nucleon. The isotopic composition for B and N is assumed to be $^{11}\text{B}:^{10}\text{B} = 0.7:0.3$ and $^{14}\text{N}:^{15}\text{N} = 0.5:0.5$ for all energies.

The distribution of $N(E)$ is derived by unfolding the distribution of total energy deposited in the TASC, $N(E_{\text{TASC}})$, to correct for significant bin-to-bin migration effects, which arise from the TASC limited energy resolution ($\sim 30\%$), and infer the primary particle energy. The response matrix for the unfolding procedure [24] is derived using MC simulations after applying the same selection procedure as for FD. The total selection efficiency $\varepsilon(E)$ remains nearly constant above 100 GeV, with different values for O ($\sim 42\%$), N ($\sim 35\%$) and B C ($\sim 25\%$), primarily due to different HE trigger efficiencies. Prior to unfolding, background contamination from misidentified neighboring nuclei is estimated as a function of E_{TASC} and subtracted from the observed distribution $N(E_{\text{TASC}})$. The contamination fraction for B (N) is approximately 1% (3%) for $E_{\text{TASC}} < 10^2$ GeV and increases logarithmically, reaching around 10% (15%) at 5 TeV. The background is negligible for C and O, remaining below 0.5% up to 2 TeV and reaching 1% at 10 TeV.

Several sources of systematic uncertainties were investigated, including trigger efficiency, charge identification, energy scale correction, unfolding procedure, MC simulations, isotopic composition, and background subtraction. The main contribution arises from the different MC simulations used in the analysis, which yield similar selection efficiencies but produce significantly different energy response matrices in both the low- and high-energy regions [23].

4. Results

4.1 Carbon and Oxygen

The energy spectra of C and O, along with their flux ratio measured with CALET, are shown in Fig. 1 and compared to previous results from space-based [1, 3, 25] and balloon-borne [2, 26, 27] experiments. These updated spectra are based on a larger dataset and align with our earlier results [5], extending the energy range to 18.9 TeV/n and including a more precise assessment of systematic uncertainties. While they generally agree with data from other experiments, the absolute normalization shows a significant discrepancy with AMS-02, although the C/O ratio remains consistent. We have investigated whether this discrepancy could stem from uncertainties in the

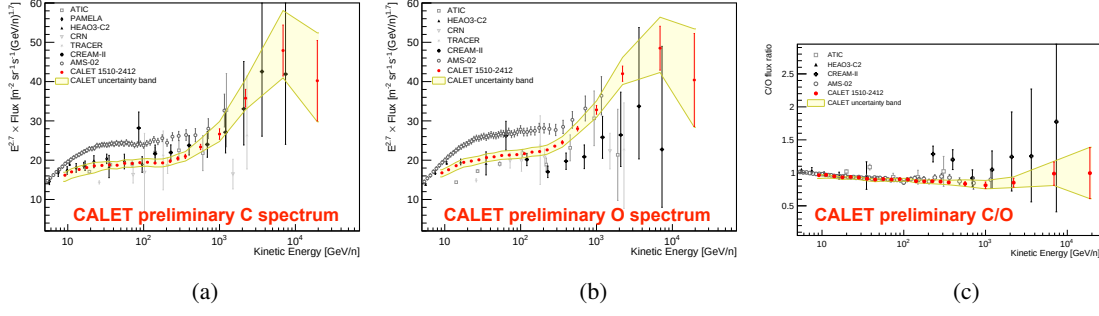


Figure 1: CALET carbon (a) and oxygen (b) flux (multiplied by $E^{2.7}$) and ratio of carbon to oxygen (c) as a function of kinetic energy per nucleon E . Error bars of CALET data (red) represent the statistical uncertainty only, while the yellow band indicates the quadratic sum of statistical and systematic errors. Also plotted are other direct measurements [1–3, 25–27].

nucleus-nucleus cross sections used in MC simulations, particularly for interactions between nuclei and PWO. To address this, we modified the cross-section for C nuclei on PWO in the simulated data, thereby altering the probability density of inelastic interactions as a function of the particle path length within the TASC. We found that adjusting the normalization of the cross-section versus energy curve resulted in a change of the overall flux normalization, but had minimal impact on the shape of the energy spectrum. Even with a 50% reduction in cross-section normalization—well beyond realistic uncertainties—the flux only increased by 15%, which remains insufficient to explain the 27% discrepancy observed with the AMS flux. This suggests that cross-section uncertainties alone are unlikely to account for the normalization difference.

As shown in Fig. 2, the energy dependence of the C and O fluxes appears very similar when their spectra are superimposed. Therefore, we fit the combined CALET C and O data using a double power-law (DPL) function

$$\Phi(E) = \begin{cases} c \left(\frac{E}{\text{GeV}} \right)^\gamma & E \leq E_0 \\ c \left(\frac{E}{\text{GeV}} \right)^\gamma \left(\frac{E}{E_0} \right)^{\Delta\gamma} & E > E_0 \end{cases} \quad (2)$$

where c is a normalization factor, γ the spectral index, and $\Delta\gamma$ the spectral index change above the transition energy E_0 . A single power-law function (SPL) is also shown for comparison, where $\Delta\gamma = 0$ is fixed in Eq. (2) and the fit is limited to data points with $25 < E < 200$ GeV/ n and extrapolated above. The simultaneous DPL fit to the C and O spectra (with common parameters, except normalization) in the energy range [25, 6700] GeV/ n yields $\gamma_{CO} = -2.66 \pm 0.02$, $\Delta\gamma_{CO} = 0.23 \pm 0.03$, and $\tilde{E}_0 = (260 \pm 40)$ GeV/ n confirming our first results [5]. Our measurements indicate a spectrum hardening with a significance greater than 7σ , as determined by a likelihood ratio test. The last two data points suggest that the hardening trend ceases at around 10 TeV/ n , which hints at a possible softening of the spectra at higher energies.

4.2 Boron

The updated boron results shown in Fig. 3 are based on increased statistics and extend the energy range up to 6.7 TeV/ n , representing an improvement over our earlier results [5, 23]. As for C and O, the absolute normalization of the B spectrum is consistent with that of PAMELA [1] and

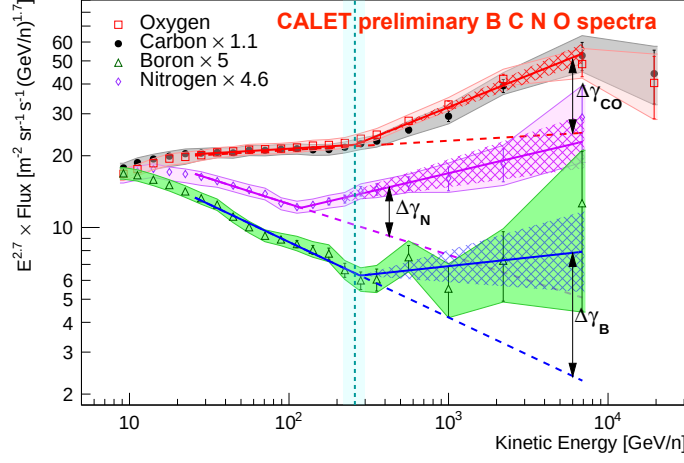


Figure 2: CALET energy spectra for BCNO are fitted with DPL functions. Each spectrum is scaled by an appropriate normalization factor to align around 10 GeV/ n for comparison. Error bars represent the statistical uncertainty only, while the coloured bands indicate the quadratic sum of statistical and systematic errors. The dashed lines represent the extrapolation of a SPL function fitted to each dataset at energies below the transition energy E_0 . The cross-shaded area shows the $\pm 1\sigma$ error interval of $\Delta\gamma$ from the fit to each dataset. The fitted value of the $\tilde{E}_0$ for CO is represented by the vertical cyan dashed line, while the cyan band shows its $\pm 1\sigma$ error interval.

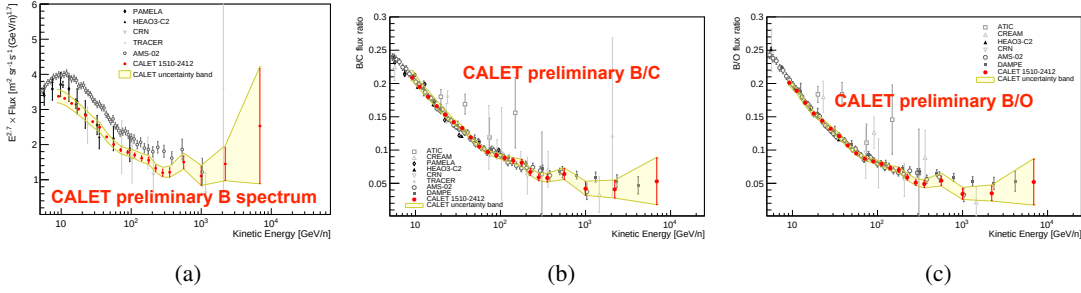


Figure 3: CALET boron (a) flux (multiplied by $E^{2.7}$) and ratio of boron to carbon (b), boron to oxygen (c) as a function of kinetic energy per nucleon E . Also plotted are other direct measurements [1–4, 25–28].

most earlier experiments, but remains lower than the value reported by AMS-02 [3]. Nevertheless, the B/C and B/O ratios are in good agreement with the AMS-02 measurements.

The B spectrum is fitted to a DPL function (Fig. 2), with the transition energy parameter E_0^B constrained to lie within the $\pm 1\sigma$ uncertainty range around the $\tilde{E}_0$ value obtained from the combined CO fit. The fit yields $\gamma_B = -3.02 \pm 0.03$ and $\Delta\gamma_B = 0.39 \pm 0.12$ with $\chi^2/\text{d.o.f.} = 5.2/11$.

As expected for primary and secondary CR, the energy spectra of B and CO differ significantly. The fit results indicate, with a statistical significance of approximately 3σ , that the B spectrum exhibits a more pronounced hardening above 200 GeV/ n compared to C and O, with a spectral index change roughly twice as large. This behavior aligns with theoretical models that attribute the spectral hardening to CR propagation effects. In galactic propagation models, secondary-to-primary ratios are expected to scale with the mean escape path length λ at high energies. Current direct measurements indicate that λ follows a power-law dependence on the kinetic energy, i.e. $\lambda(E) = kE^{-\delta}$ where δ is the spectral index of the diffusion coefficient. The observed flattening of

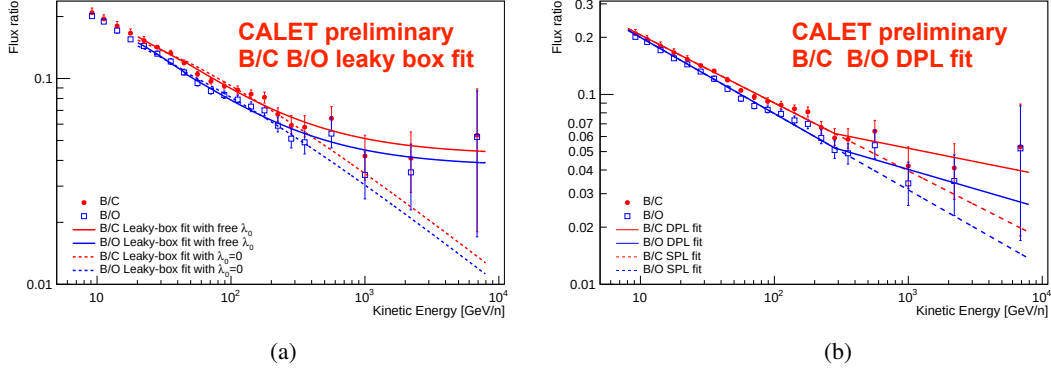


Figure 4: CALET B/C and B/O flux ratios are fitted using two approaches: (a) a "leaky-box" model where the residual path length λ_0 is either treated as a free parameter (solid line) or fixed to zero (dashed line); (b) DPL (solid lines) versus SPL (dashed lines) functions [23]. For (a), the best-fit parameters are $\delta = 0.80 \pm 0.07$ and $\lambda_0 = (1.3 \pm 0.2) \text{ g/cm}^2$ ($\chi^2/\text{d.o.f.} = 22.2/31$). When λ_0 is fixed to zero, the fit yields $\delta = 0.51 \pm 0.02$ ($\chi^2/\text{d.o.f.} = 48.8/32$). For (b), the B/C (B/O) ratio fits yield $\Gamma = -0.357 \pm 0.008$ (-0.392 ± 0.006), $\Delta\Gamma = 0.21 \pm 0.09$ (0.22 ± 0.11), $E_0 = 280 \pm 10 \text{ GeV}/n$. Error bars represent the quadratic sum of statistical and systematic uncertainties.

the B/C and B/O ratios in the TeV/ n energy range may result either from a change in the spectral index δ or from an additional residual path length λ_0 , which accounts for the amount of matter CR traverse within the acceleration region. In the first scenario, fitting B/C and B/O flux ratios with a DPL function (Fig. 4(b)) yields a spectral index change $\Delta\Gamma \sim 0.2$. In the second scenario, a simultaneous fit of B/C and B/O data using a "leaky-box" model [23] (Fig. 4(a)) gives best-fit values of $\delta = 0.80 \pm 0.07$ and $\lambda_0 = (1.3 \pm 0.2) \text{ g/cm}^2$. This result provides strong evidence in favor of a non-zero residual path length, with a statistical significance exceeding the 5σ level.

4.3 Nitrogen

Figure 5(a) shows the preliminary measurement of the N energy spectrum by CALET, extending up to 6.7 TeV/ n , significantly beyond the range explored by previous experiments. When compared to the fluxes of neighbouring elements (Fig. 2), the N spectrum exhibits a similar energy dependence to that of B at low energies. However, at higher energies, it undergoes a spectral hardening, aligning more closely with C and O spectra. A fit using a DPL function yields: $\gamma_N = -2.91 \pm 0.04$, $\Delta\gamma_N = 0.36 \pm 0.06$, and $E_0^N = (120 \pm 20) \text{ GeV}/n$ with a 5σ significance against a SPL fit. This behavior is further illustrated in the flux ratios (Figs. 5(b) and 5(c)): the N/O ratio decreases with energy before flattening as the N spectral index approaches that of O, while the N/B ratio shows a continuous hardening trend. These observations support the hypothesis that N flux has a mixed origin, comprising a primary component, $\Phi_N^p(E)$, produced in astrophysical sources, and a secondary component, $\Phi_N^s(E)$, resulting from the spallation of heavier nuclei as they propagate through the interstellar medium. Assuming that the primary component follows the spectral shape of O and the secondary component follows that of B, $\Phi_N(E)$ can be approximated as a linear combination of the O and B fluxes, and then the N/O flux ratio can be written as

$$\frac{\Phi_N(E)}{\Phi_O(E)} = \frac{\Phi_N^p(E) + \Phi_N^s(E)}{\Phi_O(E)} \simeq \frac{n_p \Phi_O(E) + n_s \Phi_B(E)}{\Phi_O(E)} = n_p + n_s \frac{\Phi_B(E)}{\Phi_O(E)} \quad (3)$$

where n_p and n_s are the relative contributions from the primary and secondary components, respectively. These coefficients can be determined by fitting the N/O ratio (Fig. 6(a)) to Eq. 3

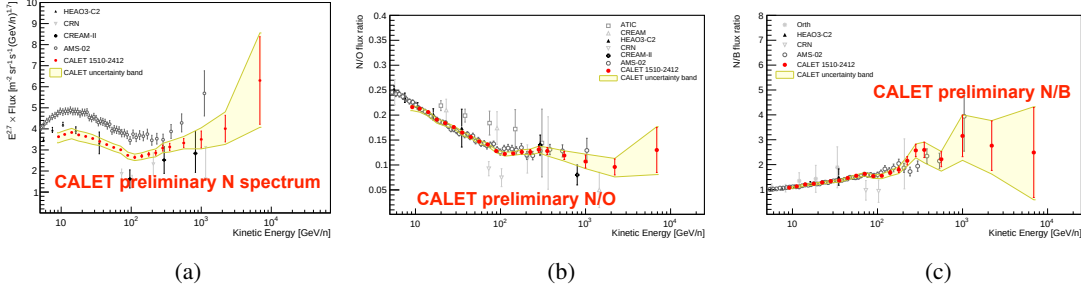


Figure 5: CALET nitrogen (a) flux (multiplied by $E^{2.7}$) and ratio of nitrogen to oxygen (b), nitrogen to boron (c) as a function of kinetic energy per nucleon E . Also plotted are other direct measurements [2, 3, 25, 28].

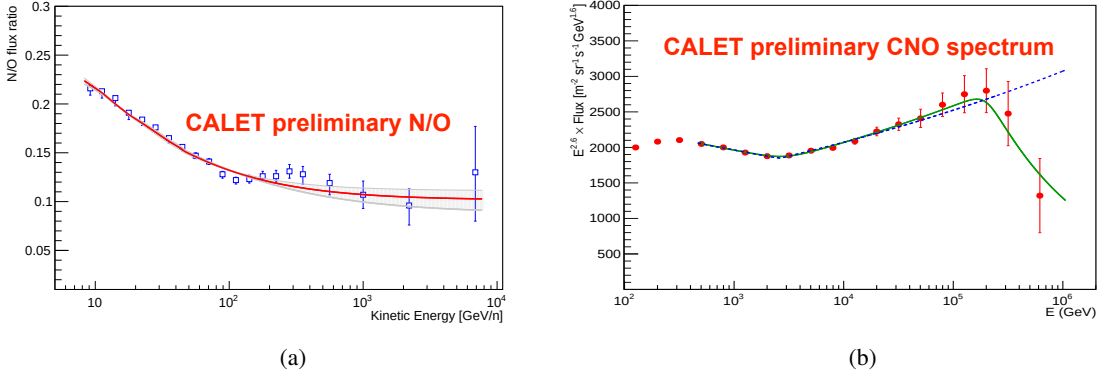


Figure 6: (a) CALET N/O flux ratio is fitted using Eq.3. Error bars represent the quadratic sum of statistical and systematic uncertainties. (b) Preliminary combined CNO spectrum fitted to a DBPL function (green line). The blue dotted line represents a fit to a single broken power-law function without the softening break.

using Φ_B/Φ_O values obtained from the B/O ratio data (Fig. 3(c)). The fit yields $n_p = 0.074 \pm 0.003$ (stat) ± 0.02 (sys) and $n_s = 0.74 \pm 0.02$ (stat) ± 0.05 (sys) ($\chi^2/\text{d.o.f.} = 27.8/21$).

4.4 Combined CNO spectrum

Although a spectral softening around 10-20 TeV has been clearly observed in the proton and He spectra [4, 5], no such feature has yet been identified in heavier nuclei. A combined analysis of C, N and O nuclei provides an effective method to explore spectral features at high energies, offering improved statistical precision and the possibility of reducing systematic uncertainties compared to analyses of individual elemental fluxes. A spectrum is calculated from a combined sample of C, N and O nuclei in CALET data, selected using criteria similar to those used for the individual element analyses, but requiring charge measurements from both CHD and IMC to fall within the range [5.5, 8.5]. However, the charge consistency cuts were slightly loosened to improve statistics, and corrections for cross-contaminations are not required. To evaluate the selection efficiency and construct the response matrix for the unfolding process, MC datasets for each nuclear species were merged using relative abundances consistent with the measured C/O and N/O ratios. A very preliminary CNO spectrum, accounting only for statistical uncertainties, is presented in Fig. 6(b). The spectrum is fitted to a double broken power-law (DBPL) function, similar to that used in proton

and He analyses [5]. The spectrum exhibits a hardening starting at ~ 3 TeV, with a spectral index change of $\Delta\gamma = 0.16 \pm 0.01$, consistent with the trends observed in the individual nuclei spectra. A hint of softening is observed around (200 ± 70) TeV, with a corresponding spectral index change of $\Delta\gamma_1 = -0.57 \pm 0.22$. The significance of the softening feature, when compared to a single broken power-law model, is at the 2.5σ level. This observation, if confirmed, would mark an important step toward understanding the high-energy behavior and limits of galactic CR accelerators.

5. Conclusion

Using 111 months of CR data collected by CALET on the ISS, we have measured the energy spectra of B and N up to 6.7 TeV/ n , and of C and O up to 18.9 TeV/ n . Our study reveals spectral hardening in the B, C and O fluxes at energies of a few hundred GeV/ n , with a more pronounced spectral index change in B than in C and O. The observed flattening of B/C and B/O ratios at TeV/ n energies can be explained by a change in the spectral index of the diffusion coefficient or the presence of source grammage. The N spectrum is consistent with a mixed composition of primary and secondary CR, exhibiting an energy dependence similar to that of B below 120 GeV/ n , gradually hardening to align with that of O spectrum at higher energies. Preliminary combined analysis of the CNO spectrum suggests a potential spectral softening around 200 TeV, which, if confirmed, would be crucial for understanding the transition region between galactic and extragalactic CR.

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