

Precision Spectral Measurements of Chromium and Titanium from 10 to 250 GeV/ n and Sub-Iron to Iron Ratio with the Calorimetric Electron Telescope on the International Space Station

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The Calorimetric Electron Telescope (CALET), in operation on the International Space Station since 2015, collected a large sample of cosmic-ray (CR) iron and sub-iron events over a wide energy interval. In this Letter, we report an update of our previous measurement of the iron flux and we present—for the first time—a high statistics measurement of the spectra of two sub-iron elements Cr and Ti in the energy interval from 10 to 250 GeV/*n*. The analyses are based on 8 years of data. Differently from older generations of cosmic-ray instruments which, in most cases, could not resolve individual sub-iron elements, CALET can identify each nuclear species from proton to nickel (and beyond) with a measurement of their electric charge. Thanks to the improvement in statistics and a more refined assessment of systematic uncertainties, the iron spectral shape is better resolved, at high energy, than in our previous paper, and we report its flux ratio to chromium and titanium. The measured fluxes of Cr and Ti show energy dependences compatible with a single power law with spectral indices -2.74 ± 0.06 and -2.88 ± 0.06 , respectively.

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Introduction—Cosmic-ray elements lying just below iron in the periodic table (sub-iron), like scandium (Sc), titanium (Ti), vanadium (V), chromium (Cr), and manganese (Mn), are thought to be mainly of secondary origin, i.e., produced by the spallation of heavier nuclei as they propagate in the interstellar medium, although for some a primary component from astrophysical sources cannot be excluded [1,2]. As such, they provide insight into cosmic-ray propagation through the Galaxy. In particular, the ratios of sub-iron elements to iron provide unique information on the average path length that cosmic rays travel before reaching Earth. The traditional “leaky box model” [3]

interpretation of secondary-to-primary ratios as a function of energy is challenged by new theoretical approaches [4–11] driven by new measurements [12–15] with unmatched precision and datasets orders of magnitude larger than earlier experiments. A number of models have been proposed to provide a comprehensive description of secondary production and acceleration including, but not limited to, an inhomogeneous or energy-dependent diffusion coefficient [4–6]; the production of a small fraction of secondaries by interactions of primary nuclei with matter inside the acceleration region [7–9]; the possible reacceleration of secondary particles during propagation [10]; and the presence of an energy-independent term in the secondary-to-primary ratio [11].

Early direct measurements of sub-iron fluxes were carried out mainly by balloon-borne instruments followed by measurements in space. The best balloon data in this charge and energy region, from Simon *et al.* [16] and Juliusson (HEN) [17] were severely limited by statistics. Satellite measurements were carried out by the Danish-French experiment [18] and the Heavy-Nuclei Experiment

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(HNE) [2], both on the HEAO-3 satellite. HNE could measure the relative abundance to Fe of individual elements from ^{18}Ar to ^{23}V and ^{28}Ni , from 10 GeV to several hundred GeV per amu, covering energies one order of magnitude larger than the Danish-French experiment (hereafter HEAO3-C2).

In the past two decades, direct measurements of charged cosmic rays from space have achieved a level of unprecedented precision with long-term observations of individual elements by AMS-02 [15,19–21], DAMPE [14], and CALET [12,22–25]. However, no high-precision measurements of individual sub-iron fluxes have yet been reported.

In this Letter, we present the fluxes of Cr and Ti measured by CALET in the energy interval from 10 to 250 GeV/ n and their ratios to iron flux using the result of an updated analysis of iron based on a larger dataset from 10 GeV/ n to 1.6 TeV/ n (see our previous publication [23]). The new results suggest the presence of a spectral hardening for iron above 200 GeV/ n .

CALET instrument—CALET is a space-based instrument [26–29] optimized for the measurement of the electron + positron spectrum [30–32] but also designed to study individual elements—from proton to iron and above—exploring particle energies up to the PeV scale, thanks to its large dynamic range, adequate calorimetric depth, accurate tracking, and excellent charge identification capabilities. CALET measures the particle’s energy with the total absorption calorimeter (TASC), a thick lead-tungstate homogeneous calorimeter (27 radiation lengths, 1.2 proton interaction lengths) preceded by a thin (three radiation lengths) preshower imaging calorimeter (IMC), both covering a very large dynamic range. Charge identification is carried out by a dedicated charge detector (CHD), a two-layered hodoscope of plastic scintillator paddles placed on top of CALET. The CHD can resolve individual elements from $Z = 1$ to $Z = 40$ with excellent charge resolution. The IMC, with 16 layers of 1 mm² square scintillating fibers (read out individually), provides tracking and an independent charge measurement, via multiple dE/dx from fibers, up to the onset of saturation which occurs for elements above ^{14}Si . Details on the instrument layout and the trigger system can be found in Supplemental Material in Ref. [30]. CALET was launched on August 19, 2015 and installed on the Japanese Experiment Module-Exposed Facility of the International Space Station (ISS). The on-orbit commissioning phase was successfully completed in the first days of October 2015. Calibration and test of the instrument took place at the CERN-SPS during five campaigns between 2010 and 2015 with beams of electrons, protons, and relativistic ions [33–35].

Data analysis—The following analyses are based on flight data (FD) collected in 2922 days of CALET operation from November 1, 2015 to October 31, 2023 aboard the ISS. The total observation live time for the high-energy (HE) shower trigger is $T \sim 5.5 \times 10^4$ h, corresponding to

86.0% of the total observation time. Periods when the field-of-view (FOV) was partially obscured by ISS mobile structures were excluded from the analysis. Each channel of CHD, IMC, and TASC is individually calibrated on orbit using a dedicated trigger mode which selects penetrating proton and helium particles [35,36]. Raw signals are corrected for gain differences among the channels, position, and temperature dependence and temporal gain variations as well as nonuniformity in light output. After calibration, a track is reconstructed for each event with an associated estimate of its charge and energy.

The particle’s direction and entrance point are reconstructed and fit by a tracking algorithm based on a combinatorial Kalman filter fed with the coordinates provided by the scintillating fibers of the IMC. It identifies the incident track in the presence of background hits generated by secondary radiation backscattered from the TASC [37]. The angular resolution is $\sim 0.08^\circ$ for Ti, Cr, and Fe, and the spatial resolution for the impact point on the CHD is ~ 180 μm .

The particle’s charge Z is reconstructed by measuring the ionization deposits in the CHD. The dE/dx samples are extracted from the signals of the CHD paddles traversed by the incident particle and properly corrected for their path length. Either CHD layer provides an independent dE/dx measurement. In order to correct for the reduction of the scintillator’s light yield due to the quenching effect, a “halo” model [38] has been used to fit the FD samples of each nuclear species as a function of Z^2 . The resulting curves are then used to reconstruct a charge value in either layer (Z_{CHDX} , Z_{CHDY}) on an event-by-event basis [22].

The presence of an increasing amount of backscatters from the TASC at higher energy generates additional energy deposits in the CHD that add up to the primary particle ionization signal and may induce an incorrect charge identification. This effect causes a systematic displacement of the CHDX-CHDY charge peaks to higher values (up to $0.8e$ in charge units) with respect to the nominal charge position. Therefore, it is necessary to restore the nuclei peak positions to their nominal values by an energy-dependent charge correction applied separately to the FD and the simulated (MC) data. Thanks to the large statistics collected during the first 8 years of operation, it was possible to correct for this effect in the iron and sub-iron region up to a deposited energy in the TASC (E_{TASC}) of 40 TeV. A charge distribution obtained by averaging Z_{CHDX} and Z_{CHDY} is shown in Fig. 1. The CHD charge resolution σ_Z for iron is $\sim 0.35e$.

For each event, the shower energy is calculated as the sum of the energy deposits of all TASC logs, after merging the gain ranges of each channel [36].

The quenching effect in the TASC logs has been included in the MC simulation by extracting a quenching correction function from the flight data. Further details on this can be found in Supplemental Material of Ref. [23].

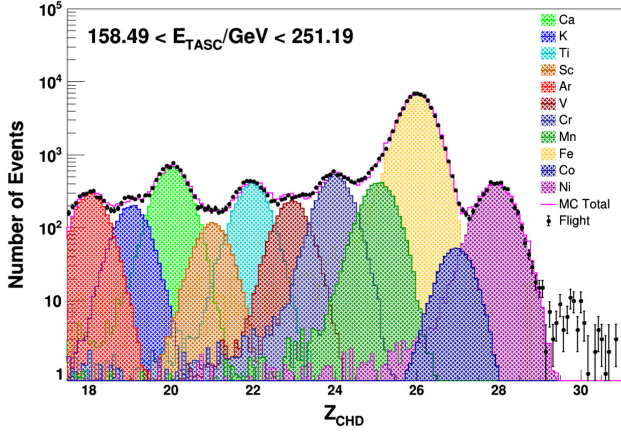


FIG. 1. Charge distributions from the combined charge measurement of the two CHD layers in the elemental region between Ar and Zn. Events are selected with $158.49 < E_{\text{TASC}} < 251.19$ GeV. Flight data (black dots) are compared with Monte Carlo samples comprising Ar, K, Ca, Sc, Ti, V, Cr, Mn, Fe, Co, and Ni. In Fig. S1 in Supplemental Material [39], an enlarged version of this figure is shown.

Only events with a well-fitted primary track crossing the detector from CHD top to TASC bottom are used for these analyses. The geometrical factor of the fiducial region is $S\Omega \sim 510 \text{ cm}^2 \text{ sr}$.

The onboard HE trigger based on the coincidence of the summed dynode signals of the last four IMC layers with the TASCX1 layer has an efficiency close to 100% for elements heavier than oxygen as the threshold is far below their signal amplitude at minimum ionization. Therefore, an off-line trigger confirmation, as required for the analysis of lighter elements [22,40], is not necessary for these analyses. However, we require a deposited energy larger (by 2 standard deviations) than at minimum ionization in at least one of the first four layers of the TASC. This is adopted to select the shower events which interact in the upper part of the TASC (shower event cut).

Particles undergoing a charge-changing nuclear interaction in the upper part of the instrument are removed by applying a selection based on their track width (TW) and by requiring that the difference between the charges from either layer of the CHD is less than $1.0e$ ($1.5e$ for iron). TW is defined as the difference, normalized to the particle charge, between the total energy deposited in the ± 3 fibers nearest to the fiber crossed by the reconstructed track and the sum of the signals of the two fibers adjacent to it. Examples of TW distributions are shown in Fig. S3 in Supplemental Material [39]. Iron events are selected within a wider ellipse than the one used in our previous publication [23]: It is centered at $Z = 26$, with $2\sigma_x$ - and $2\sigma_y$ -wide semiaxes for Z_{CHDX} and Z_{CHDY} , respectively, rotated clockwise by 45° as shown in the cross plot of the CHDY vs CHDX charge in Fig. S2 in Supplemental Material [39]. Titanium and chromium events, instead,

are selected in CHDY vs CHDX plane within a circle centered at $Z = 22$ and $Z = 24$, with a radius $R = 0.55e$ and $R = 0.45e$, respectively. Event selections are identical for flight data and MC.

The FOV of CALET ($< 45^\circ$) is partially shielded at large zenith angle by fixed structures of the ISS. Moreover, moving structures (e.g., solar panels and robotic arms) can cross the FOV for short periods of time during ISS operations. CR interactions in these structures can create secondary nuclei that may induce a contamination of the flux measurement. Inside the fiducial geometrical factor, 8% of the final candidate events have reconstructed trajectories pointing to moving structures, and they are discarded in the analyses. Applying the aforementioned cuts, 7.4×10^3 Ti, 6.1×10^3 Cr, and 1.2×10^5 Fe candidate events are selected.

An iterative unfolding Bayesian method [41] is applied to correct the distributions of the total energy deposited in the TASC (E_{TASC}) for significant bin-to-bin migration effects (due to the limited energy resolution) and infer the primary particle energy. The response matrix used in the unfolding procedure is derived using MC simulations after applying the same selection procedure of the FD, and it is shown in Fig. S6 in Supplemental Material [39].

The energy spectrum is obtained from the unfolded energy distribution as follows:

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

$$N(E) = U[N_{\text{obs}}(E_{\text{TASC}}) - N_{\text{bg}}(E_{\text{TASC}})], \quad (2)$$

where ΔE denotes the energy bin width, E is the geometric mean of the lower and upper bounds of the bin [42], $N(E)$ is the bin content of the unfolded distribution, $\epsilon(E)$ is the total selection efficiency (Fig. S4 in Supplemental Material [39]), $S\Omega$ is the geometrical factor, T is the live time, $U()$ is the unfolding procedure operator, $N_{\text{obs}}(E_{\text{TASC}})$ is the bin content of the observed energy distribution (including background), and $N_{\text{bg}}(E_{\text{TASC}})$ are the background events in the same bin. Background contamination from different nuclear species misidentified as Ti (Cr, Fe) is shown in Fig. S5 in Supplemental Material [39]. The contamination fraction $N_{\text{bg}}/N_{\text{obs}}$ for Fe is very low in the whole energy range ($< 2\%$). Instead, the contaminations for Ti and Cr are larger, though limited to $< 11\%$ in the E_{TASC} energy range between 100 and 4000 GeV.

Systematic uncertainties—The total systematic error was computed as the sum in quadrature of all the sources of systematics in each energy bin, both energy dependent and energy independent. The energy dependence (in GeV/ n) of systematic uncertainties is shown in Fig. S8 in Supplemental Material [39] for Ti, Cr, and Fe. The sources of energy-dependent systematic error include (i) charge identification, (ii) energy scale correction, (iii) unfolding

procedure, (iv) shower event selection, (v) background subtraction, and (vi) track width selection. The systematic error related to the charge identification for Cr and Ti (Fe) was studied by varying the values of the semiminor and major axes of the charge cut up to 30% (50%). The result was a flux variation for Cr and Ti of a few percent below 100 GeV/ n , increasing within -15% to 10% at 200 GeV/ n . The iron flux variation ranges from -3% to 3% , depending on the energy bin. The uncertainty ($\pm 2\%$) on the energy scale from the beam test calibration affects the absolute normalization of the Cr, Ti, and Fe spectra by $\pm 3.5\%$ but not their shape. The uncertainty due to the unfolding procedure was evaluated by using different response matrices computed by varying the spectral index of the generation spectrum of MC simulations. The resulting fluxes did not show appreciable variations. The contribution due to the shower event cut, which rejects

noninteracting particles, becomes significant only at low energies (4%–5% below 30 GeV/ n). The systematic error related to the background contamination for Cr and Ti is assessed by varying the contamination level up to $\pm 3\sigma$ of the statistical error. For Fe, due to lower background, the contamination level is varied up to $\pm 50\%$. The result was Cr and Ti fluxes variation around a few percent below 100 GeV/ n , increasing to 10% at 200 GeV/ n ; the iron flux normalization remains stable within 1% in the whole energy range. The uncertainty on the track width selection leads to a maximum error of 5% in the Ti flux above 200 GeV/ n and $\sim 2\%$ below. Additional energy-independent systematic uncertainties affecting the fluxes normalization include live time (3.4%) and long-term stability ($< 2\%$).

Results—The energy spectra of Ti, Cr, and Fe and their flux ratio measured with CALET are shown in Figs. 2 and 3, respectively; the corresponding data tables including statistical and systematic errors are reported in Supplemental Material [39].

CALET Cr and Ti spectra are compared with results from HEAO3-C2 [18] and HEN [17] experiments. The CALET Fe spectrum turns out to be consistent with most of the previous measurements within the uncertainty error band, in both spectral shape and normalization with the exception of the AMS-02 [19] iron flux measurement, which has a very similar shape, but differs in the absolute normalization by $\sim 20\%$ [22,23]. Instrumental effects that may cause this tension are under investigation. The Fe spectrum shown here is based on a factor of 2 larger dataset than in our previous publication and on an improved charge

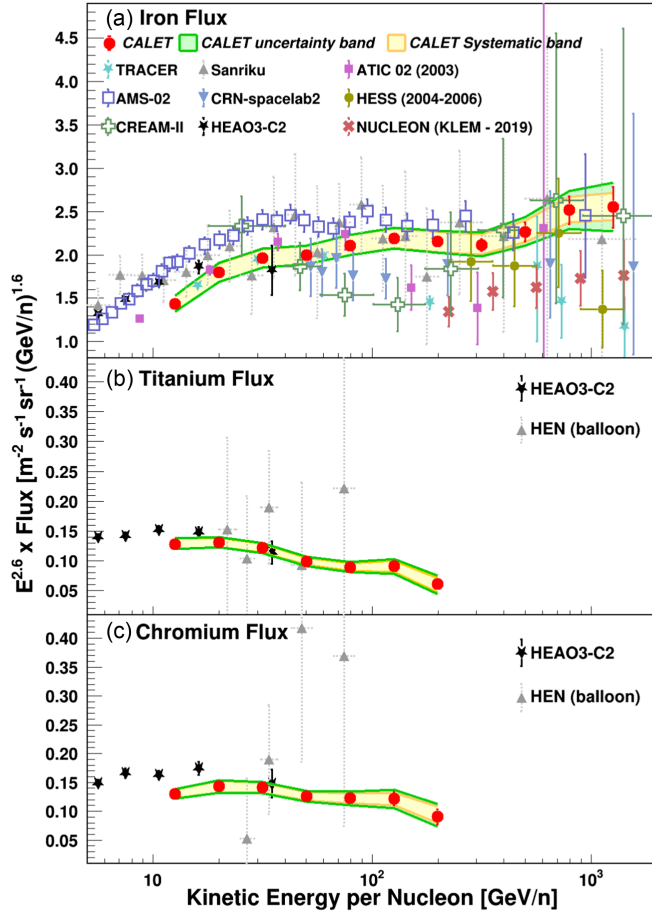


FIG. 2. CALET (a) Fe, (b) Ti, and (c) Cr flux (multiplied by $E^{2.6}$), as a function of kinetic energy per nucleon. The error bars of the CALET data (red filled circles) represent the statistical uncertainty only, and the yellow band the quadrature sum of systematic errors, while the green band the quadrature sum of statistical and systematic errors. Also plotted are other direct measurements [17–19,43–49]. An enlarged version of the figure is shown in Fig. S9 in Supplemental Material [39].

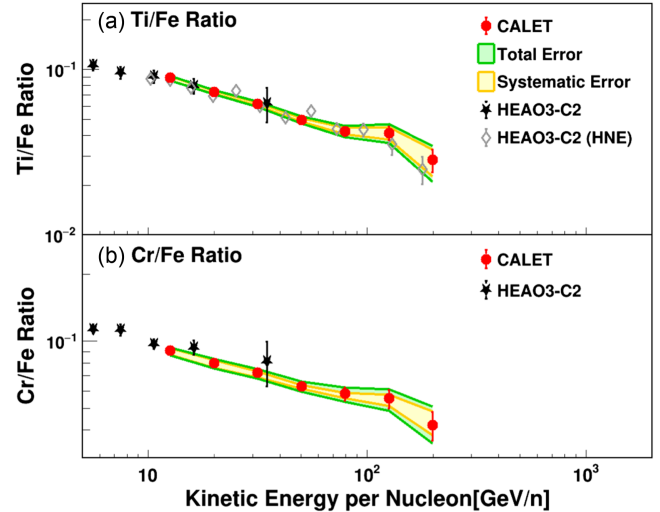


FIG. 3. CALET (a) Ti/Fe and (b) Cr/Fe ratio as a function of kinetic energy per nucleon. The error bars of the CALET data (red filled circles) represent the statistical uncertainty only, and the yellow band the quadrature sum of systematic errors, while the green band the quadrature sum of statistical and systematic errors. Also plotted are the HEAO3-C2 [18] and HNE [50] direct measurements.

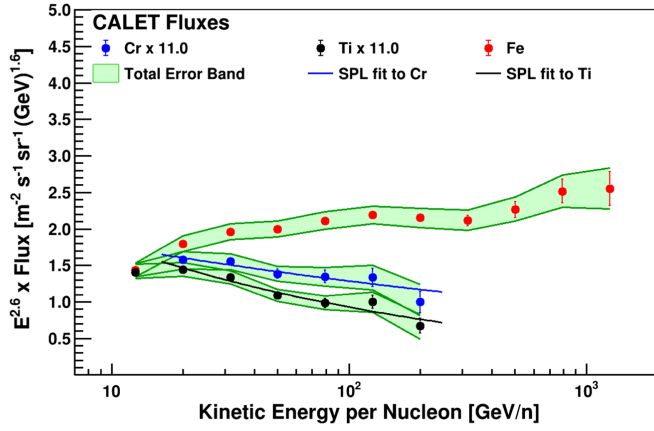


FIG. 4. CALET Cr (blue) and Ti (black) energy spectra are fitted with a SPL function in the energy range [16–250] GeV/n; the CALET Fe spectrum (red) is reported for comparison. The Ti and Cr spectra are multiplied by a factor of 11 in order to compare them with the iron spectrum. Here, the green bands indicate the total error.

calibration: It is consistent with our earlier result up to 400 GeV/n but differs from it at higher energy, suggesting a possible hardening of the spectrum above a few hundred GeV/n.

Figures 3(a) and 3(b) show the Ti/Fe and the Cr/Fe ratio, respectively. Also shown are the results from HEAO3-C2 [18] and HNE [50] experiments. The two sets of data are in good agreement in the energy interval where they overlap, [10–30] GeV/n. Figure 4 shows the fits to CALET Ti and Cr data with a single power-law function (SPL) $\Phi(E) = C[E/(\text{GeV}/n)]^\gamma$, where C is a normalization factor and γ the spectral index. The fit is performed from 16 to 250 GeV/n for both Cr and Ti. The fit gives $\gamma_{\text{Ti}} = -2.88 \pm 0.06$ (stat $\oplus$ syst) with $(\chi^2/\text{d.o.f.})_{\text{Ti}} = 1.8/4$ for Ti and $\gamma_{\text{Cr}} = -2.74 \pm 0.06$ (stat $\oplus$ syst) with $(\chi^2/\text{d.o.f.})_{\text{Cr}} = 1.1/4$ for Cr.

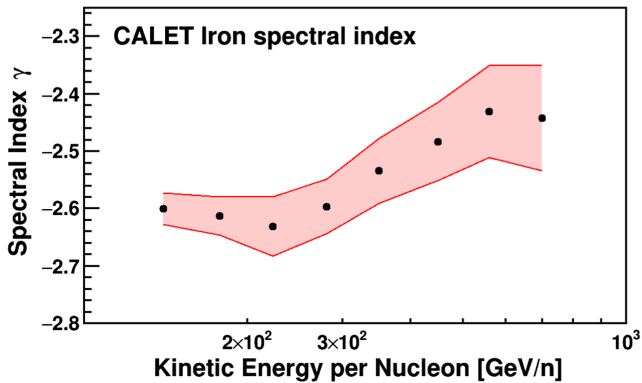


FIG. 5. Energy dependence of the iron spectral index calculated with CALET data within a sliding energy window centered on each energy bin and including ± 2 neighboring bins. The shaded area is representative of the uncertainty due to purely statistical errors.

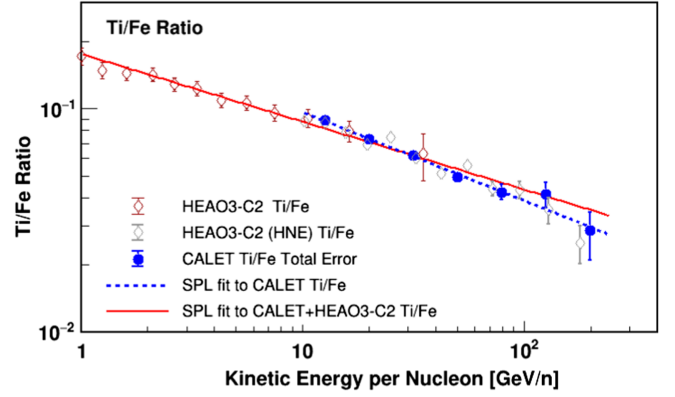


FIG. 6. Combined fit of CALET and HEAO3-C2 [18] Ti/Fe ratio with a SPL function (red line) in the energy range [1–250] GeV/n. Also shown is the fit to the CALET data alone using a SPL function (blue dashed line) in the energy range [10–250] GeV/n. The error bars of the CALET data represent the total error. The results of HNE experiments [50] (magenta diamonds) are shown for comparison.

An indication of iron spectral hardening is suggested in Fig. 5, where the spectral index is plotted as a function of kinetic energy per nucleon. We used the iron flux with ten bins per decade (see Fig. S7 in Supplemental Material [39]) to calculate the spectral index γ above 100 GeV/n by a fit of $d[\log(\phi)]/d[\log(E)]$ within a sliding window centered on each energy bin and including the ± 2 neighboring bins.

Figures 6 and 7 show the fits to CALET Ti/Fe and Cr/Fe ratio in the energy range [10–250] GeV/n with a SPL fit (blue dashed lines). The best-fit spectral indices for these two ratios are $\gamma_{\text{Ti/Fe}} = -0.39 \pm 0.03$ and $\gamma_{\text{Cr/Fe}} = -0.24 \pm 0.03$ with a $\chi^2/\text{d.o.f.}$ of 1.9/5 and 0.8/5, respectively. Also shown in Figs. 6 and 7 are the fits obtained by combining the data from both CALET and HEAO3-C2 experiments in

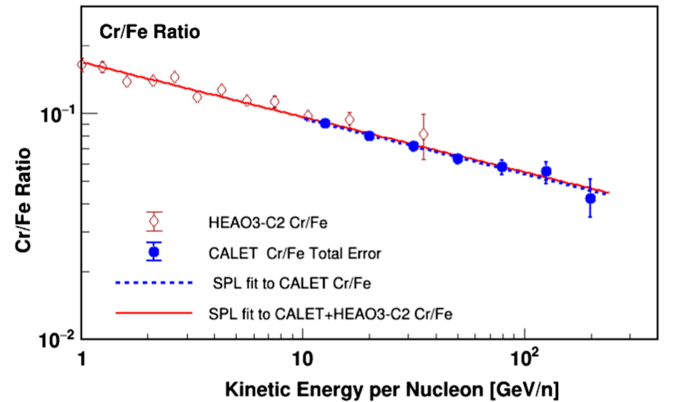


FIG. 7. Combined fit of CALET and HEAO3-C2 [18] Cr/Fe ratio with a SPL function (red line) in the energy range [1–250] GeV/n. Also shown is the fit to the CALET data alone using a SPL function (blue dashed line) in the energy range [10–250] GeV/n. The error bars of the CALET data represent the total error.

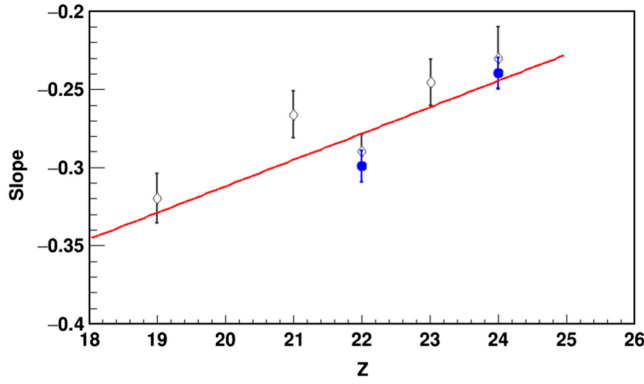


FIG. 8. Dependence on atomic number Z of the spectral indices of flux ratios to iron. The combined HEAO3-C2 and CALET data on Ti/Fe and Cr/Fe (blue filled circles) are compared with the combined HEAO3-C2 and HNE data (black diamonds) [2,50]. The red line is the result of a linear fit to the seven plotted points.

the energy range [1–250] GeV/ n using with a SPL (red lines): In this case, the fit gives $\gamma_{\text{Ti/Fe}} = -0.30 \pm 0.01$ with a $(\chi^2/\text{d.o.f.})_{\text{Ti/Fe}} = 15/17$ and $\gamma_{\text{Cr/Fe}} = -0.24 \pm 0.01$ with a $(\chi^2/\text{d.o.f.})_{\text{Cr/Fe}} = 17/17$. The dependence of these indices on the atomic number Z and a comparison with the result obtained by fitting HEAO3-C2 with HNE data are shown in Fig. 8. The variation of the index with Z , as reported in [2,50], is found to be consistent with the combined HEAO3-C2 and CALET data on Ti and Cr flux ratios to Fe.

Conclusion—In this Letter, we present a measurement of the energy spectra of sub-iron elements chromium and titanium from 10 to 250 GeV/ n , as well as their ratio to iron, with a significantly enhanced precision compared to the existing measurements. Our results suggest that the titanium and chromium fluxes, as well as their ratio to iron, are consistent with a SPL within the range of our measurements. Beyond this limit, we will try to extend the observations to draw a significant conclusion regarding a potential deviation from a single power law. The Cr/Fe and Ti/Fe ratios, along with their spectral indices, align with the findings of the HNE and HEAO3-C2 experiments. The improvement in statistics with respect to our previous publication [23] and a more refined assessment of calibrations and systematics errors have allowed a better determination of the iron spectral shape at high energy, suggesting the possibility of a deviation from a single power law at an energy exceeding 200 GeV/ n .

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Data availability—The data that support the findings of this Letter are not publicly available upon publication because it is not technically feasible and/or the cost of preparing, depositing, and hosting the data would be prohibitive within the terms of this research project. The data are available from the authors upon reasonable request.

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