

Elemental energy spectra of cosmic rays measured by CREAM-II

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Abstract. We present new measurements of the energy spectra of cosmic-ray (CR) nuclei from the second flight of the balloon-borne experiment CREAM (Cosmic Ray Energetics And Mass). The instrument (CREAM-II) was comprised of detectors based on different techniques (Cherenkov light, specific ionization in scintillators and silicon sensors) to provide a redundant charge identification and a thin ionization calorimeter capable of measuring the energy of cosmic rays up to several hundreds of TeV. The data analysis is described and the individual energy spectra of C, O, Ne, Mg, Si and Fe are reported up to $\sim 10^{14}$ eV. The spectral shape looks nearly the same for all the primary elements and can be expressed as a power law in energy $E^{-2.66\pm 0.04}$. The nitrogen absolute intensity in the energy range 100-800 GeV/n is also measured.

Keywords: Cosmic-ray nuclei, energy spectrum, composition, balloon experiments

I. INTRODUCTION

CREAM is a balloon-borne experiment designed to directly measure the elemental composition and the energy spectra of cosmic rays from H to Fe in the energy range 10^{11} - 10^{15} eV. CREAM aims to experimentally test astrophysical models proposed to explain the acceleration mechanism of cosmic rays and their propagation in the Galaxy [1].

Since 2004, four instruments were successfully flown on long-duration balloons in Antarctica. The instrument configurations varied slightly in each mission, due to various detector upgrades. In this paper, we describe the procedure used to analyze the data collected during the second flight and reconstruct the energy spectra of the major primary CR nuclei and nitrogen. Results are

compared with other direct observations and discussed.

II. THE CREAM-II INSTRUMENT

The instrument for the second flight included: a redundant system for particle identification, consisting (from top to bottom) of a timing-charge detector (TCD), a Cherenkov detector (CD), a pixelated silicon charge detector (SCD), and a sampling imaging calorimeter (CAL) designed to provide a measurement of the energy of primary nuclei in the multi-TeV region.

The TCD is comprised of two planes of four 5 mm-thick plastic scintillator paddles, read out by fast photomultiplier tubes (PMTs) and covering an area of 120×120 cm². It was designed to determine each element charge with a resolution $\lesssim 0.35 e$ (units of the electron charge) and discriminate against albedo particles [2]. The CD is a 1 cm-thick plastic radiator, with 1 m² surface area, read out by eight PMTs via wavelength shifting bars. It is mainly used to flag relativistic particles. The SCD is a dual layer of 312 silicon sensors, each segmented as an array of 4×4 pixels which covers an effective area of 0.52 m² with no dead regions. It is capable of resolving individual elements from H to Ni with a fine charge resolution [3]. The CAL is a stack of 20 tungsten plates (50×50 cm² and 1 radiation-length thick) interleaved with active layers of 1 cm-wide scintillating fiber ribbons, read out by 40 hybrid photodiodes [4]. A $0.47 \lambda_{int}$ -thick graphite target precedes the CAL, and serves to induce hadronic interactions of the CR nuclei. The electromagnetic (e.m.) core of the resulting hadronic cascade is imaged by the CAL which is sufficiently thick to contain the shower maximum and grained finely enough to reconstruct the direction of the incident particle.

CREAM-II was launched on Dec. 16th 2005 from

McMurdo and floated over Antarctica for 28 days, at a balloon altitude of 35 to 40 km. All the detectors performed well in flight. The data acquisition was enabled by the trigger system whenever a shower developing in at least 6 planes was detected in the CAL or a relativistic cosmic ray with $Z \geq 2$ was identified by the TCD and CD. A total of 57 GB of data were collected. A detailed description of the instrument and its performance in flight is given in [5].

III. DATA ANALYSIS

The present analysis uses a subset of data collected in the period Dec. 19th- Jan. 12th, having stable instrument conditions. In order to measure the elemental energy spectra, each detected CR particle has been assigned a charge and an energy. An accurate reconstruction of the particle trajectory through the instrument is needed for the charge determination.

A. Trajectory reconstruction

The axis of the shower imaged by the calorimeter can be measured to determine the arrival direction of a CR nucleus. Candidate track points are sampled along the longitudinal development of the shower. They are defined as the center of gravity of the cluster formed in each CAL plane by the cell with the maximum signal and its two neighbours. A track is built by matching the candidate points and the shower axis parameters are calculated with a linear χ^2 fit of the track. Track quality is assessed by requiring a value of $\chi^2 < 10$. The reconstructed shower axis is back-projected through the graphite target to its intersections with the two SCD layers. These define the impact points of the primary particle, with a spatial resolution better than 1 cm rms.

B. Charge assignment

In each SCD layer, the pixel with the highest signal is sought inside a fiducial circle with a 3 cm radius centered on the impact point. In order to achieve high purity samples of CR elements, the signals of the two selected pixels are required to be consistent within 30%. In such a case, the two independent samples of the specific ionization dE/dx are then corrected for the pathlength (estimated from the track parameters) traversed by the particle in the silicon sensors. The accuracy of the pathlength correction is improved by adding the matched SCD pixels to the track points and refitting them again. By combining the two corrected measures of dE/dx , the primary particle charge Z is estimated. The charge distribution reconstructed by the SCD is shown in Fig. 1; by fitting each peak to a gaussian, a charge resolution σ is estimated as: 0.2 e for C, N, O; $\sim 0.23 e$ for Ne, Mg, Si; $\sim 0.5 e$ for Fe. Samples of each element up to Si are selected with a 2σ cut around the mean charge value, while for iron a 1σ cut is used. In this way, 1288 O are retained, as well as 456 Si and 409 Fe candidates.

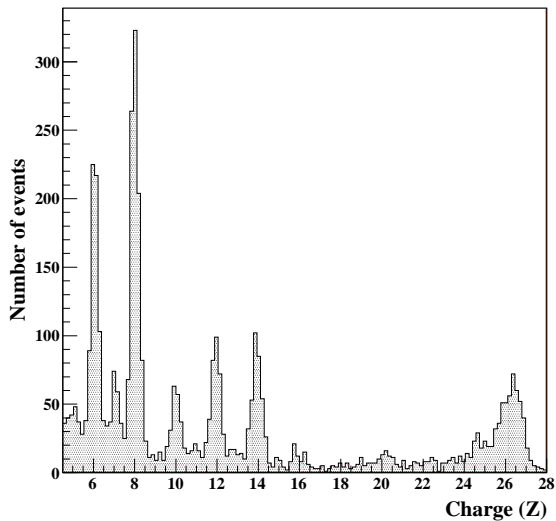


Fig. 1: Charge histogram obtained by the SCD in the elemental range from B to Fe. The distribution is only indicative of the SCD charge resolution and the relative elemental abundances are not meaningful.

C. Energy measurement and deconvolution

The CREAM thin ionization calorimeter samples the e.m. core of the hadronic cascade initiated by a cosmic ray interacting in the target. According to the results of tests with particle beams [6] and Monte Carlo (MC) simulations based on the FLUKA 2006.3b package [7], though a significant part of the cascade energy leaks out of the calorimeter, the primary particle energy still scales linearly with the energy deposited in the CAL by the shower core up to several hundreds of TeV. The total energy deposit is measured by summing up the calibrated signals of all the CAL cells. Once each cosmic ray is assigned an energy, the reconstructed particles of each nuclear species are sorted into energy intervals with width commensurate with the rms resolution of the calorimeter.

Due to the finite energy resolution of the detector, of the order of 30% for heavy nuclei with energy > 1 TeV, an unfolding procedure has to be applied to correct the measured counts in each energy interval for overlap with the neighbouring bins. This requires solving a set of linear equations

$$M_i = \sum_{j=1}^n A_{ij} N_j \quad i = 1, \dots, m$$

relating the “true” counts N_j of n incident energy bins to the measured counts M_i of m deposited energy bins. A generic element of the mixing matrix A_{ij} represents the probability that a CR particle, carrying an energy corresponding to a given energy bin j , produces an energy deposit in the calorimeter falling in the bin i . The unfolding matrix elements are estimated by analyzing MC simulated CR events with the same procedure as that used for the flight data.

IV. ENERGY SPECTRUM

The absolute differential intensity Φ at the top of the atmosphere is calculated by dividing the unfolded number of events N_i by the bin width ΔE_i , according to the formula

$$\Phi(\hat{E}_i) = \frac{N_i}{\Delta E_i} \times \frac{1}{\epsilon \times \text{TOI} \times \text{TOA} \times S\Omega \times T}$$

where T is the exposure time, ϵ the efficiency of the selection cuts, $S\Omega$ the geometric factor of the instrument, and TOI and TOA are, respectively, the corrections to the top of instrument and to the top of the atmosphere. Each bin is centered at a median energy \hat{E}_i calculated as described in [8].

The geometric factor $S\Omega$ is estimated to be $0.46 \text{ m}^2\text{sr}$ from MC simulations. The selected set of data amounts to a live time T of 16 days and 19 hours, close to 75% of the real time of data taking, as measured by the housekeeping system onboard. The MC estimated overall reconstruction efficiency ϵ has a constant value of around 70% at energies $> 3 \text{ TeV}$ for all nuclei.

The probability that a nucleus undergoes a spallation reaction in the material ($\sim 4.8 \text{ g/cm}^2$) above the upper SCD plane is also estimated from MC simulations. The fraction of surviving nuclei, i.e., the TOI correction, spans from 81.3% for C to 61.9% for Fe. The TOA correction is calculated by simulating with FLUKA the atmospheric overburden during the flight (3.9 g/cm^2 on average). Survival probabilities ranging from 84.2% for C to 71.6% for Fe are found.

The TOI and TOA corrections take into account only the loss of primary particles interacting in the atmosphere and in the instrument materials. Furthermore, the counts N_i for each species are corrected for the gain of secondary particles produced by spallation reactions of heavier CR nuclei. These corrections are of the order of few percent for all the considered elements but nitrogen. In fact, $\sim 30\%$ of the observed N nuclei originate from the spallation of much more abundant oxygen.

V. RESULTS

The differential intensity at the top of the atmosphere as measured by CREAM-II for the major primary CR nuclei from carbon to iron is plotted as a function of the kinetic energy per nucleon in Fig. 2. The nitrogen energy spectrum (multiplied by $E^{2.5}$) is shown in Fig. 3. The error bars in the intensity are calculated as the sum in quadrature of the error due to the counting statistics and the systematic uncertainties.

The main systematic uncertainties stem from the reconstruction algorithm and from the TOI and TOA corrections. In the first case, the fractional systematic error is estimated to be of order 10% in the energy bins below 3 TeV and 5% above. The systematic error for the uncertainty in correcting the differential intensity to the top of instrument is 2% for the primary elements. For nitrogen, a 15% error is assigned because of the

large contamination of O nuclei which spallate into N. Similar values are estimated for the systematic error deriving from the uncertainties in the atmospheric secondary corrections.

In summary, the particle energy range measured by CREAM-II extends from around 800 GeV up to 100 TeV. The absolute intensities are presented without any arbitrary normalization to previous data and cover a range of six decades.

VI. DISCUSSION

The CREAM-II results for primary nuclei are found in general to be in good agreement with previous measurements of space-based (HEAO-3-C2 [9], CRN [10]) and balloon-borne (ATIC-2 [11], TRACER [12]) experiments. A power-law fit $E^{-\gamma}$ to our data indicates that the intensities of the more abundant evenly charged heavy elements have a very similar energy dependence. That is, their spectra are characterized, within errors, by nearly the same spectral index γ . Our observations, based on a calorimetric measurement of the CR energy, confirm the results recently reported by the TRACER collaboration, using completely different techniques to determine the particle energy. The weighted average of the fitted spectral indices (Fig. 2) is $\bar{\gamma} = 2.66 \pm 0.04$, consistent, within the error, with the value of 2.65 ± 0.05 obtained from a fit to the combined CRN and TRACER data [12]. The great similarity of the spectral indices suggests that the same mechanism is responsible for the source acceleration of the primary heavy nuclei, assuming, as common, that the escape pathlength of primary elements from the galaxy does not depend on the particle charge for primary elements.

The nitrogen data collected by CREAM-II are statistically more significant at high energy than any previous observation. Unlike the primary heavy nuclei, nitrogen is mostly produced by spallation in the interstellar medium but also has a primary contribution of order 10%, as recently measured by CREAM-I [14]. We notice that, at energies above 100 GeV/n, the nitrogen spectrum flattens out from the steep decline which characterizes the energy range 10-100 GeV/n. This supports the hypothesis of the presence of two components in the cosmic nitrogen. In fact, since the escape pathlength decreases rapidly with energy, the secondary nitrogen is expected to become negligible at high energy, where only the primary component should remain. This might result in a change of the spectral slope, as observed.

To provide a check to our measurements, we calculate the relative abundance ratio of N/O and compare it with the CREAM-I result. A N/O ratio (at the top of the atmosphere) equal to 0.080 ± 0.025 (stat.) ± 0.025 (sys.) is measured at an energy of $\sim 800 \text{ GeV/n}$, in good agreement with the CREAM-I result [14].

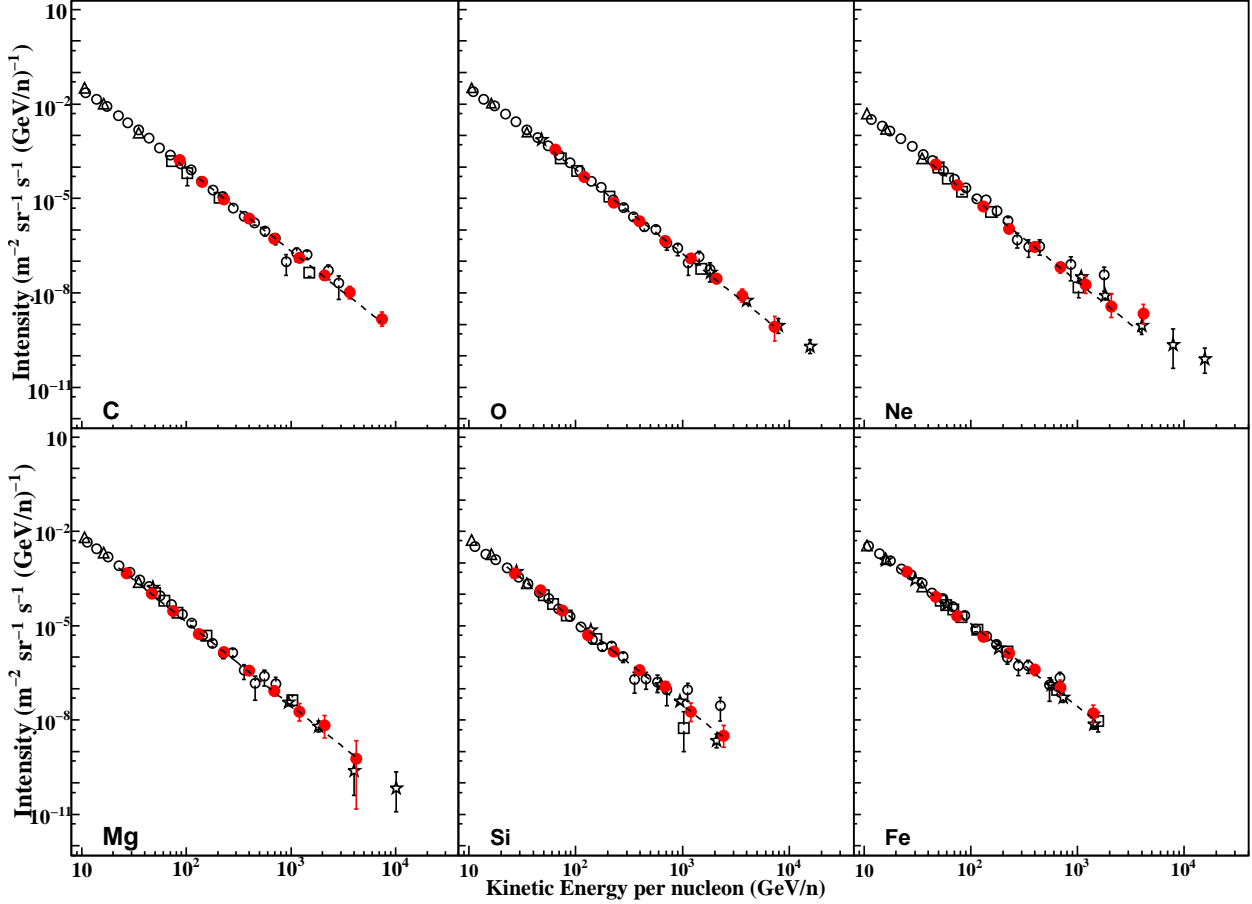


Fig. 2: Energy spectra of the more abundant heavy nuclei. Results of CREAM-II (filled circles) are compared with measurements from HEAO-3-C2 [9] (triangles), CRN [10] (squares), ATIC-2 [11] (open circles), TRACER [12] (stars). The dashed line represents a power-law fit to the CREAM-II data. The fitted values of the spectral indices are, respectively: C 2.61 ± 0.07 ; O 2.67 ± 0.07 ; Ne 2.72 ± 0.11 ; Mg 2.66 ± 0.08 ; Si 2.67 ± 0.08 ; Fe 2.63 ± 0.12 .

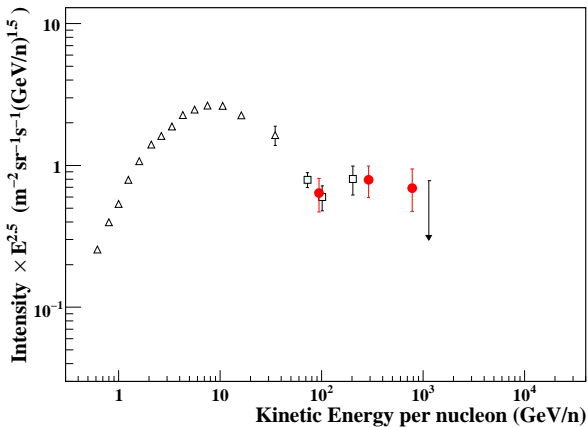


Fig. 3: Nitrogen energy spectrum multiplied by $E^{2.5}$. CREAM-II results (*filled circles*) are compared with previous observations by HEAO-3-C2 [9] (*triangles*) and CRN [13] (*squares*). The arrow is an upper limit set by CRN at 1.1 TeV/n.

VII. CONCLUSION

The CREAM-II instrument carried out measurements of high Z cosmic ray nuclei with an excellent charge resolution and a reliable energy determination. The energy spectra of the major primary heavy nuclei from C to Fe were measured up to 10^{14} eV and found to agree well with earlier direct measurements. A new measurement of the nitrogen intensity in an energy region thus far experimentally unexplored indicates a less steep power-law trend in the spectrum with respect to lower energies.

ACKNOWLEDGMENTS

This work is supported by NASA, NSF and CSBF in USA, INFN and PNRA in Italy, KICOS and MOST in Korea.

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