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Cosmic-ray Heavy Nuclei Spectra Using the ISS-CREAM Instrument

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Cosmic Ray Energetics And Mass for the International Space Station (ISS-CREAM) was designed to study high-energy cosmic rays up to PeV and recorded data from August 22nd, 2017 to February 12th, 2019 on the ISS. In this analysis, the Silicon Charge Detector (SCD), CALorimeter (CAL), and Top and Bottom Counting Detectors (TCD/BCD) are used. The SCD is composed of four layers and provides the measurement of cosmic-ray charges with a resolution of ~0.2e. The CAL comprises 20 interleaved tungsten plates and scintillators, measures the incident cosmic-ray particles' energies, and provides a high energy trigger. The TCD/BCDs consist of photodiode arrays and plastic scintillators and provide a low-energy trigger. In this analysis, the SCD top layer is used for charge determination. Here, we present the heavy nuclei analysis using the ISS-CREAM instrument.

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1. Introduction

Cosmic-ray heavy nuclei include both primary and secondary cosmic-rays. Astrophysical sources directly produce primary cosmic-rays, and secondary cosmic-rays are produced from collisions of primary cosmic-rays with the interstellar medium. The investigation of cosmic-ray heavy nuclei can provide the keys to the propagation and acceleration mechanisms of cosmic rays [1–3].

The balloon-borne Cosmic-Ray Energetics And Mass (CREAM) experiment reported important results such as spectral hardening around 200 GeV/nucleon [4]. The CREAM payload was transformed for accommodation on the International Space Station (ISS) after the last flight in 2016. This version of CREAM, aka ISS-CREAM, was launched on August 14, 2017, aboard the SpaceX CRS-12 Dragon spacecraft. The ISS-CREAM experiment recorded cosmic-ray data from August 22, 2017 to February 12, 2019, which is used in the paper's heavy nuclei analysis.

2. ISS-CREAM Instrument

The ISS-CREAM instrument consists of several sub-detectors, as shown in Fig. 1. In this analysis, the Silicon Charge Detector (SCD), CALorimeter (CAL) and Top, and Bottom Counting Detectors (TCD/BCD) are used. The SCD measures the charge of cosmic-ray particles and consists of 4 layers, each with a 78.2 cm × 73.6 cm active area [5]. Each layer has 2688 small silicon pixels, 1.38 cm × 1.55 cm in size, to reduce the effect of backscattered particles.

The CAL consists of 20 layers that consist of tungsten plates and fifty scintillating-fiber ribbons [6]. The surface area of each layer is 50 × 50 cm^2. The length of the CAL is 20 X_0 radiation lengths. Because the scintillating-fiber ribbons alternate directions in each layer, the CAL not only measures the energy of cosmic-ray particles, it also reconstructs tracks from particle showers. Additionally, the CAL provides a high energy trigger when cosmic-ray particles leave signals exceeding a threshold in 6 consecutive layers.

The TCD/BCDs each consist of 20 × 20 photodiode arrays and plastic scintillators [7]. The TCD/BCDs measure showers' longitudinal and lateral profiles as they are placed above and below the CAL with two-dimensional photodiode arrays. Also, the TCD/BCD provides a trigger when cosmic rays leave signals exceeding a threshold that is lower than the CAL threshold. The lower threshold means that the TCD/BCD triggers on lower-energy cosmic rays than the CAL.

3. Data Analysis

All 539 days of ISS-CREAM data are used in this analysis. Particle tracks path length and SCD hit positions are reconstructed using CAL shower profiles. Path length corrections are applied to the SCD silicon pixels for measurements of the cosmic-ray charges. Additional details are in the following sub-sections.

3.1 Track Reconstruction

Event tracks are reconstructed when signals in six consecutive layers in the CAL have a signal above a threshold. The positions of the scintillating fibers with the maximum ADC signal in each

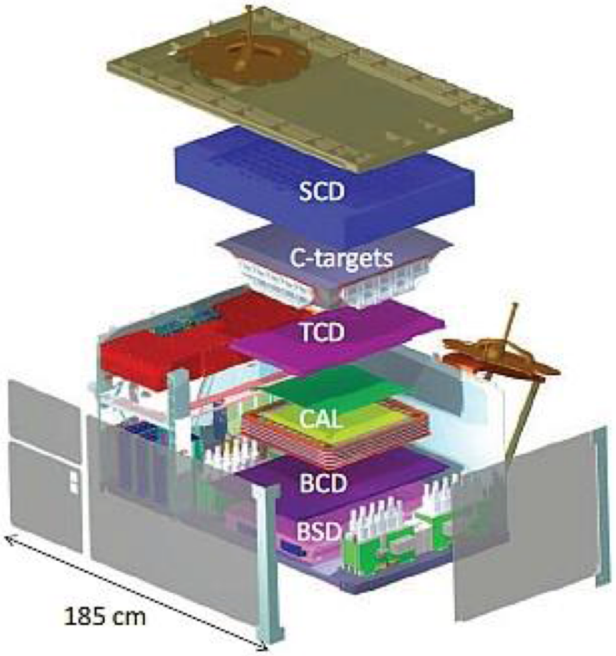

Figure 1: Schematics of the ISS-CREAM instrument, composed of the SCD, carbon targets, TCD/BCD, CAL, and BSD [8].

layer are used for track reconstruction in the x-z and y-z planes. The initial hit positions of cosmic-ray particles in each detector are extrapolated from the reconstructed track. Using Monte-Carlo (MC) simulated data, the hit position resolution can be found by comparing the reconstruction to the actual hit position. Those hit positions are well matched as shown in Fig. 2.

3.2 Charge Determination

The incident cosmic-ray particle hit location is found by backtracking the reconstructed track to the SCD. Because of tracking uncertainties due to the long lever arm from the CAL, we use the maximum ADC signal in an 11.1 cm × 11.5 cm area centered at the extrapolated CAL track. A path length correction is applied to what because deposited energies in detectors depend on the path length of cosmic-ray particles. The first SCD layer (SCD1) signals are used for charge identification in this analysis. The charge distribution from carbon to iron is shown in Fig. 3. Individual elements are separated with a resolution of 0.25e for carbon and 0.26e for oxygen. Heavy nuclei events were selected in ranges based on the SCD signals. For charge Z, particles measured with Z ± 0.5 are selected.

3.3 Energy Deconvolution

Due to the finite energy resolution of the CAL, cosmic-rays with the same incident energy can deposit different energies in the detector; therefore, an energy correction must be applied to each deposited energy bin. The distribution measured by the CAL is deconvolved into an incident energy distribution by using response matrices [9]. The relation between incident energy and deposited

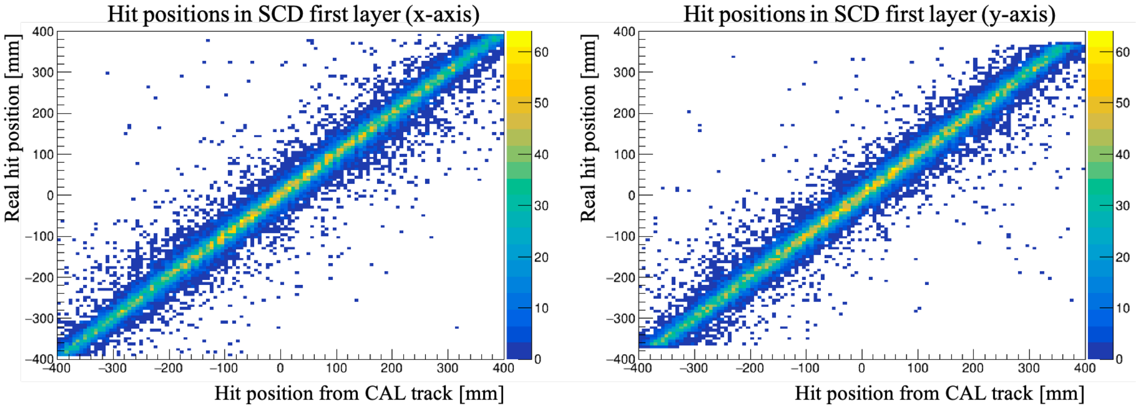

Figure 2: Scatter plots of real hit positions and reconstructed hit positions at SCD1. Reconstructed hit positions are well matched with real hit positions in both the x and y axes.

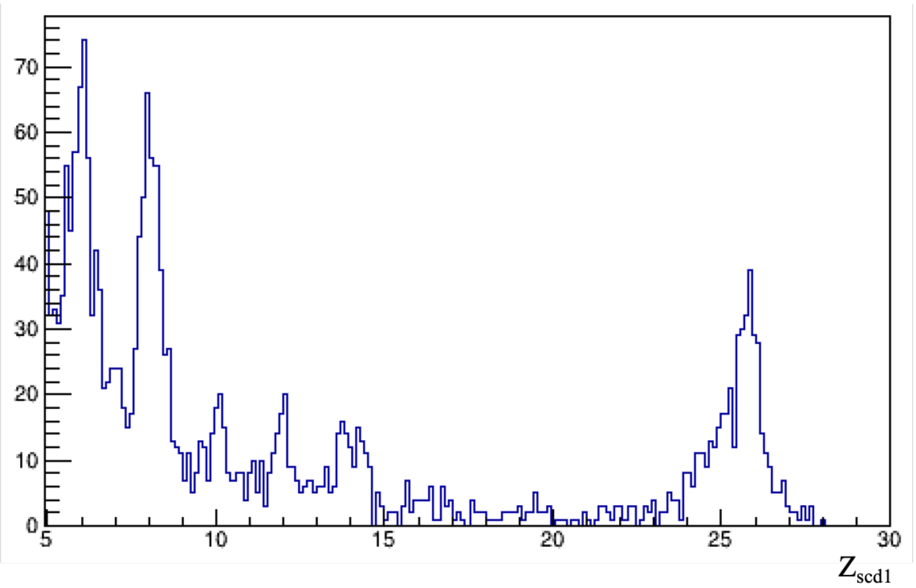

Figure 3: The charge distribution for carbon to iron nuclei measured with the ISS-CREAM SCD1. The relative abundance in this plot does not have physical significance as corrections for interactions and propagation have not been applied.

energy is described using the equation below

$$N_{inc,i} = \sum_j P_{i,j} N_{dep,j}, \tag{1}$$

where $N_{dep,j}$ is the number of events in deposited energy bin j, $P_{i,j}$ is the probability that events in deposited energy bin j are from incident energy bin i. $N_{inc,i}$ is the number of events in incident energy bin i. The $P_{i,j}$ can be described using the response matrices as shown in Fig. 4. Carbon and oxygen Geant4 MC simulation data with the QGSP_BIC physics list have been used to make the matrices. The number of events in each incident bin follows a power-law. The deposited energies

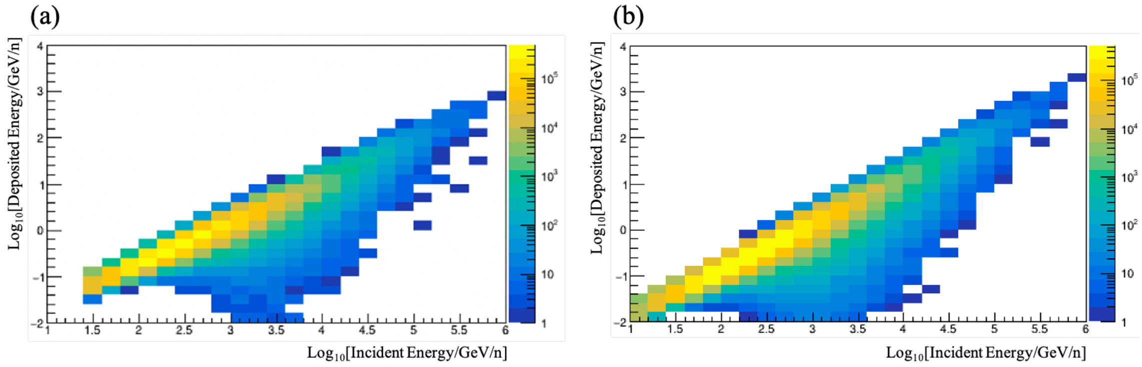

Figure 4: Response matrices for carbon (a) and oxygen (b) calculated from MC simulation data. The deposited energy distribution for each incident energy bin is generated by MC simulations.

of carbon and oxygen nuclei in the ISS-CREAM flight data range from ~0.1 to ~100 GeV/n. The response matrices are generated to cover an energy deposit range of ~0.01 to ~1000 GeV/n that allows at least an order of magnitude margin to void any edge effect in the deconvolution process. Variations between MC models are currently being investigated.

4. Results

Each cosmic-ray events estimated charge number Z is determined from the SCD1 charge distribution. The mean deposited energies in the CAL from incident energies for protons determine the incident energies in this paper [10]. The differential energy spectra of each element are found by dividing the number of events in each energy bin by the bin size. The differential spectra from carbon to iron are shown in Fig. 5 All nuclei spectra show power-law like distributions. Note that corrections for efficiencies have not yet been applied. Efficiencies for the trigger, track reconstruction, and event selections are in the process of being estimated.

5. Conclusion

The ISS-CREAM instrument was launched successfully and recorded data for 539 days from August 22, 2017, to February 25, 2019. Analysis of cosmic-ray heavy nuclei from carbon to iron is reported in this paper. In the future, an energy deconvolution method will be applied to consider the energy resolution of the CAL. To improve the charge determination accuracy, the consistency of charge values between the top two layers of the SCD will be compared. The measured differential spectra will be corrected for geometry factors, live time, and efficiencies to get the absolute fluxes.

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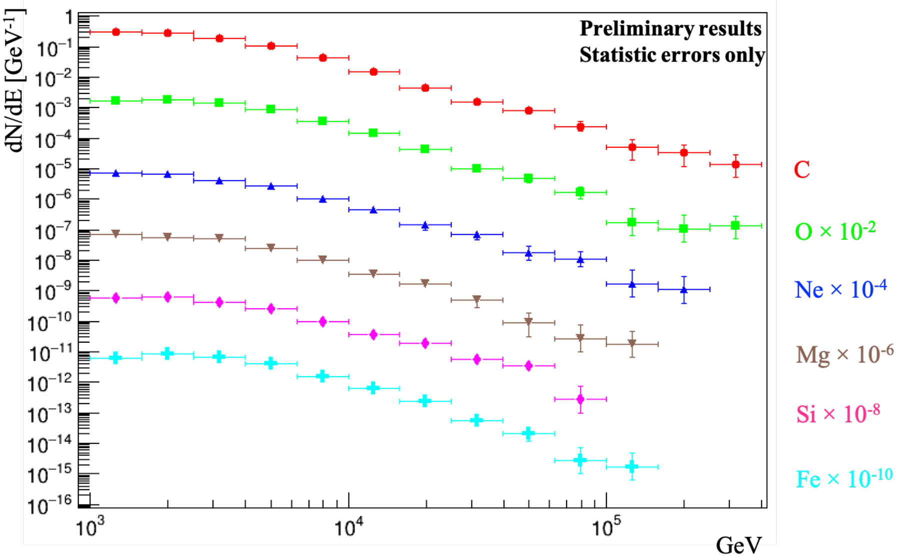

Figure 5: The differential spectra of heavy nuclei from carbon to iron: red circle, carbon; green square, oxygen; blue triangle, neon; brown inverted triangle, magnesium; pink diamond, silicon; and sky-blue cross, iron. The error bars include only statistical errors.

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