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Measurements of High-Energy Heavy Nuclei with the CREAM-I TRD

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Abstract: The balloon-borne cosmic-ray experiment CREAM-I (Cosmic-Ray Energetics And Mass) completed a successful 42-day flight during the 2004-2005 CSBF Antarctic expedition. CREAM-I combines an imaging calorimeter with charge detectors and a precision transition radiation detector (TRD). The TRD component of CREAM-I is targeted at measuring the energy of cosmic-ray particles with charges greater than Z$\sim$3. A central science goal of this effort is the determination of the ratio of secondary to primary nuclei at high energy. This measurement is crucial for the reconstruction of the propagation history of cosmic rays and consequently, for the determination of their source spectra. Initial results from the TRD portion of the science stack will be presented.

Introduction

The Cosmic-Ray Energetics and Mass instrument is a balloon-borne payload designed to make direct measurements of the energy and elemental composition of cosmic rays at high energies. The first flight of this instrument took place during the 2004-2005 CSBF Antarctic balloon campaign and was successfully completed in January of 2005, after 42 days afloat (see [1]).

The CREAM payload comprises a suite of complementary instruments, including charge and velocity detectors, a gas transition radiation detector, and a thin Tungsten/scintillating-fiber sampling calorimeter. The inclusion of multiple instruments allows for cross-calibration and reduction of systematic errors. Here we discuss results obtained using the "Hi-Z" subset of detectors, which is specifically designed to measure particles with nuclear charge $Z >\sim 3$. This detector set includes the TRD, the Cerenkov velocity detector and the timing charge detector (TCD). The data presented here also make use of the silicon charge detector (SCD), which is located underneath the TRD stack.

Science Goals

One of the primary scientific goals of the CREAM project is the measurement of primary and secondary cosmic ray nuclei at high energies. The ratio of these fluxes reveals information about the propagation history (*e.g.*, the amount of material traversed) of the primary particles.

Previous measurements have shown (see, *e.g.*, [2] and [3] and references therein) that this ratio appears to drop in a manner which is consistent with a simple power-law rigidity-dependent (*i.e.*, $\propto R^{-\delta}$) model of escape from the Galaxy ([4]). As a result, the cosmic-ray energy spectrum is modified such that the power-law spectral index is flatter at the particle source by an amount δ. Current data on the ratio of Boron to Carbon (B/C) extend up to ~ 200 GeV/nuc, and appear to favor $\delta \sim 0.6$, which, when combined with the observed index of the overall energy spectrum (~ 2.7), matches well to the predicted source spectra from diffusive shock acceleration models (*i.e.*, ~ 2.1). Consistent results have been obtained from the study of the sub-Fe (Z=21 to Z=24) to Fe ratio (*e.g.*, [3, 5]).

Extending these measurements to higher energies, with improved statistics, is one of the central goals of CREAM, and will help determine whether this ratio continues to drop as seen at lower energies, or whether some new behavior will be exhibited.

Instrument Design & Performance

A detailed description of all of the CREAM components can be found in [6]; here we briefly review the design and performance of the Hi-Z system: the TCD, the TRD and the Cerenkov detector.

Charge Detectors

The TCD system includes 8 scintillator paddles arranged into orthogonal X & Y layers. The paddles are 1.2m-long, 5mm-thick slabs of Bicron BC-408 read out with Photonis XP2020UR fast photomultiplier tubes through twisted-strip BC-802 adiabatic light guides. Each paddle is viewed on both ends by a photomultiplier tube.

The signals from the TCD, in conjunction with the Cerenkov detector, are used to generate the instrument's Hi-Z trigger, and (again jointly) to measure the charge of incoming particles. The requirements for the charge resolution are set by the need to resolve populations of adjacent secondary and primary elements, over the entire relevant charge range. In this flight, resolutions of ~ 0.2e were achieved for Oxygen and ~ 0.35e for Iron. See [7] for more details.

Similar charge resolution is achieved by the silicon charge detector system [8]. Since this system is located beneath the full TRD stack, it is very useful as a veto against charge-changing particle interactions which can occur in the body of the TRD.

Cerenkov Detector

The CREAM Cerenkov detector consists of a 1.4 cm-thick 1.2m x 1.2m acrylic sheet doped with blue wavelength shifter. This radiator is surrounded by 4 bars of wavelength-shifting plastic butted against the 4 edges of the sheet. The ends of each bar are viewed with photomultipliers, providing a compact detector with a relatively uniform response (it is flat to $\sim$ 2% over $\sim 95\%$ of the detector area, after corrections).

The Cerenkov threshold of the radiator material is $\gamma \sim 1.35$ and the participation of the Cerenkov detector in the instrument trigger enables the rejection of the many low-energy particles in the cosmic ray flux at high latitudes. The signals in this detector also provide information complementary to the TCD on the charge of the incident primary particles.

Transition Radiation Detector

The CREAM TRD is constructed of 512 thin-walled gas proportional tubes filled with a mixture of 95% Xenon/5% Methane at 1 atmosphere. The 2 cm-diameter tubes are 1.2 meters long and are wound from thin (100μm) mylar to allow easy penetration by the relatively low-energy transition radiation x-rays. The tubes are fixed in a matrix of polystyrene foam radiator and arranged in 8 layers of 64 tubes, with alternating orthogonal X and Y orientations. The signals from each tube are read out with a simple dual-gain system utilizing two channels of an Amplex 1.5 ASIC, achieving better than 11-bit overall effective dynamic range.

The TRD is designed to provide a measurement of the Lorentz factor of the primary particle as it traverses the detector, and hence it is configured as a precision TRD (see, *e.g.*, [9]), rather than a threshold TRD. Accurate trajectory information is crucial for applying proper response map corrections to the TCD and Cerenkov systems. The TRD can provide excellent particle tracking, producing a 3D particle trajectory which, using the simplest linear reconstruction methods, can achieve an RMS position resolution of $\sigma \sim 5$ mm. A second-level likeli-

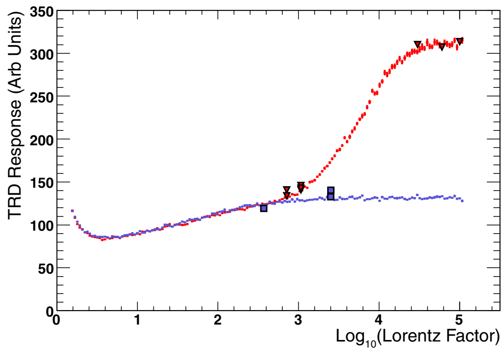

Figure 1: GEANT4 simulations of gas detector response. The lines show the simulation response with (red) and without (blue) a transition radiator present. The red triangles and blue squares show the response measured in a beam-test at CERN with and without a radiator, respectively.

hood fit which takes the tube geometry, impact parameters, and energy deposition distributions into consideration can improve this to better than 2 mm. See [10] for details.

Another important property of the TRD tracking system is the precision with which energy loss per unit pathlength over the entire track can be determined. This resolution has a direct impact on the ultimate energy resolution achievable with the instrument, and must be sufficiently good to achieve the science goals of the mission. By using the X and Y projections of the TRD tubes as independent detectors, however, we are able to test this resolution and compare it to Monte Carlo simulations. Such an analysis suggests the dE/dx resolution for non-interacting Oxygen nuclei is $\sim 8\%$ RMS.

Energy Calibration

The energy of incident primary nuclei can be determined by examining the rate of ionization energy deposit in the TRD system. At energies below ~ 1 TeV/nucleon, the determination relies on the logarithmically-increasing "relativistic rise" of ionization energy loss, which is relatively large in Xenon (plateau/MIP ~ 1.5). Above this energy, the additional contribution from x-ray transition radiation photons improves the measurement, up to Lorentz factors of $\gamma \sim 20000$.

With a minor modification to the code (which simply doubles the number of transition radiation photons produced) the GEANT4 simulation package also appears to properly reproduce the production of transition radiation at higher Lorentz factors. Figure 1 shows a comparison of Monte Carlo results to data collected in a beam-line test in 2001 at CERN ([11]). Here, the upper and lower lines show, respectively, the simulated gas detector response with and without a transition radiator volume inserted in the beam-line. The rise in the upper line above $\log_{10}(\gamma) \sim 3$ is due to the onset of transition radiation production. On this plot, the red triangles and blue squares indicate measurements made during the beam-test with and without a radiator volume present. These tests confirm that our energy calibration at high energy is adequate.

Results and Discussion

After calibrating the detector response curves, the measured energy deposit in the Hi-Z detector systems can be used to reconstruct the energy of the incident cosmic ray events. This, along with the charge information collected by the TCD and SCD systems allows us to produce energy-dependent ratios of secondary to primary nuclei. Figure 2 shows the preliminary results of this procedure for the ratio of Boron to Carbon and Nitrogen to Oxygen. In these figures, the energy is reconstructed with the TRD system and pure elemental samples are ensured by strict charge-agreement cuts between the TCD and SCD detectors. Overlap corrections which account for the finite energy resolution of the detectors have been applied and the bin sizes have been selected to be $\sim 2\sigma$ wide in energy resolution. A correction for the production of secondary nuclei in the atmospheric overburden of the detector has also been applied.

Also shown on the plots are results from the HEAO experiment [3]). Where there is overlap between the experiments, the agreement is satisfactory. Each plot also contains three lines representing three variations of a simple leaky box calculation. In each panel, a single parameter in the model has been varied to produce three different predictions. For the left panel (B/C), three power-law indices (0.33, 0.6, 0.7) for the rigidity dependence of the cosmic ray escape length have been plotted. The data fall close to the 0.6 line, though the error bars (which are statistical) are still large. For the right panel (N/O), the power-law index for escape

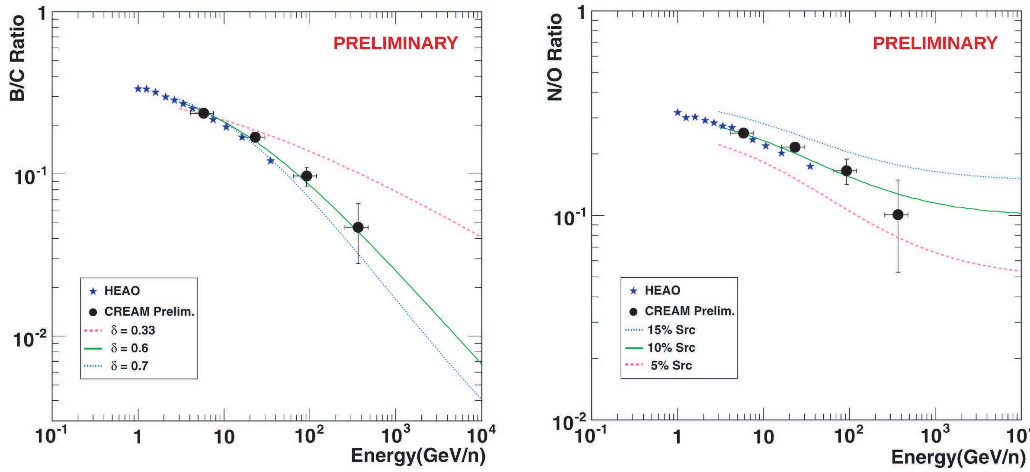

Figure 2: Preliminary secondary to primary ratios, as measured with the CREAM instrument. The left panel shows the ratio of Boron to Carbon nuclei vs energy; the right panel shows the ratio of Nitrogen to Oxygen. In both panels, the filled circles are the CREAM data and the stars represent data collected by the HEAO experiment ([3]). The overlaid lines represent the predicted results from various models, as indicated in the legend. More information is contained in the text.

is fixed at 0.6, and instead the N/O source abundance ratio has been varied. In this case, the data seem to favor a larger source abundance.

Conclusions

The first results of the Hi-Z system of the CREAM-I instrument have been presented. After a 42-day flight during which the whole detector operated stably and efficiently, a preliminary analysis of the data indicates that the individual detectors performed very well. Furthermore, the response of the Hi-Z system appears to match the Monte Carlo simulations, and hence the response of the detectors can be well calibrated, although additional work is underway to guarantee all systematic effects are accounted for. Preliminary results on the energy-dependent ratios of Boron to Carbon and Nitrogen to Oxygen have been presented. They are in agreement with the previous high-statistics results from the HEAO experiment where there is energy overlap, and do not deviate significantly from the predictions of a simple leaky box model with $\delta \sim 0.6$. Please see [7] for acknowledgements.

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