



## 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 NSBF 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 (CREAM) instrument is a balloon-borne instrument 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 NSBF Antarctic balloon campaign and was successfully completed in January of 2005, after 42 days afloat (see [3]).

The CREAM payload comprises a suite of complementary instruments, including charge and velocity detectors, a gas transition radiation detector (TRD), 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.

### 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.*, [8] and [2] 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 ([5]). 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  $\delta$ . Current data on the ratio of Boron to Carbon (B/C) extend up to  $\sim 200$  GeV/nuc, and appear to favor  $\delta \sim 0.6$ , which, when combined with the observed index of the overall energy spectrum ( $\sim 2.7$ ), matches well to the predicted source spectra from diffusive shock acceleration models. Similar results have been obtained from the study of the sub-Fe ( $Z=21$  to  $Z=24$ ) to Fe ratio (*e.g.*, [2]).

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, or whether it approaches some constant value at high energies.

## Instrument Design & Performance

A detailed description of all the CREAM components can be found in [4]; here we briefly review the design and performance of the Hi-Z system: the TCD, the TRD and the Cerenkov detector.

### Timing Charge Detector

The TCD system includes 8 scintillator paddles arranged into orthogonal X & Y layers. The paddles are 1.2m-long, 5mm-thick slabs of Bicon BC-408 read out with Photonis XP2020UR fast photomultiplier tubes (PMTs) 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  $\sim 0.2e$  were achieved for Oxygen and  $\sim 0.35e$  for Iron. For more details, see T. Brandt et al. (these proceedings).

### Cerenkov Detector

The CREAM Cerenkov detector consists of a 1 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. These bars shift the blue radiator photons into the green wavelength range, where they are read out with 2 photomultipliers, one at each end of the bars. This design provides 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 roughly  $\gamma \sim 1.35$  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 ( $100\mu\text{m}$ ) 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. Additionally, the TRD can provide 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. Accurate trajectory information is crucial for applying proper response map corrections to the TCD and Cerenkov systems.

Monte Carlo simulations indicate that with very simple linear fitting algorithms, the TRD can provide an RMS tracking resolution of  $\sigma \sim 5$  mm. A second-level likelihood fit which takes the tube geometry, impact parameters, and energy deposition distributions into consideration can improve this to better than 2 mm. This is demonstrated in Figure 1, which shows the results of a Monte Carlo verification of the tracking accuracy.

Another important component 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 through-going Oxygen nuclei is an acceptable  $\sim 8\%$  RMS.

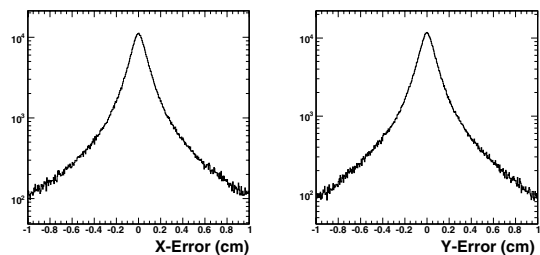


Figure 1: Simulated TRD tracking error for incident Oxygen nuclei. The left pane shows the reconstruction error in x direction. The right pane shows the reconstruction error in the y direction. In both panes, note the ordinate scale is logarithmic.

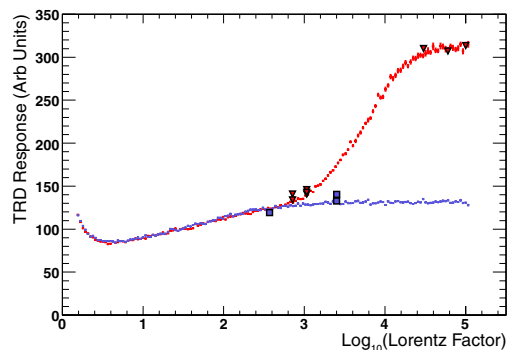


Figure 2: GEANT4 simulations of gas detector response. The lines show the simulation response with (red) and without (blue) a transition radiator present. The red triangles and blue squares show the response measured in a beam-test at CERN with and without a radiator.

### 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  $\sim 1$  TeV/nucleon, the determination relies on the logarithmically-increasing “relativistic rise” of ionization energy loss, which is relatively large in Xenon (plateau/MIP  $\sim 1.5$ ). 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 pho-

tons produced) the GEANT4 simulation package also appears to properly reproduce the production of transition radiation at higher Lorentz factors. Figure 2 shows a comparison of Monte Carlo results to data collected in a beam-line test in 2001 at CERN ([6]). Here, the red and blue lines show, respectively, the simulated gas detector response with and without a transition radiator volume inserted in the beam-line. The rise in the red 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 also adequate.

### Results and Discussion

After calibrating the detector response curves, as discussed above, the measured energy deposit in the Hi-Z detector systems can be used to reconstruct the energy of the incident cosmic ray events. Figure 3 shows the preliminary results of this procedure for Carbon and Oxygen nuclei. In these figures, the energy as reconstructed using the Cerenkov determination of  $\beta$  is indicated with blue stars, while the energy as determined using the relativistic rise in the TRD gas detectors is indicated with the green circles. Overlap corrections which account for the finite energy resolution of the detectors have been applied and the bin sizes have been selected to be  $\sim 1.5\sigma$  wide in energy resolution. As shown, the two differing techniques show good agreement where they overlap ( $\sim 10^{11}$  eV).

Also shown on the plots are the results of two space-based missions, the HEAO experiment (black squares - [2]) and the CRN experiment (red crosses - [7]). The CREAM results have been arbitrarily normalized (with a single normalization constant across all four measurements) to match the HEAO flux at around  $\sim 4$  GeV/nuc. Still, the overall agreement between the three experiments is rather good. The results for the Oxygen spectrum also agree with recent results from the TRACER instrument ([1]). Remarkably, the CREAM results span over three orders of magnitude.

Though the results presented in Figure 3 extend only up to  $\sim 1$  TeV/nuc, the total exposure factor

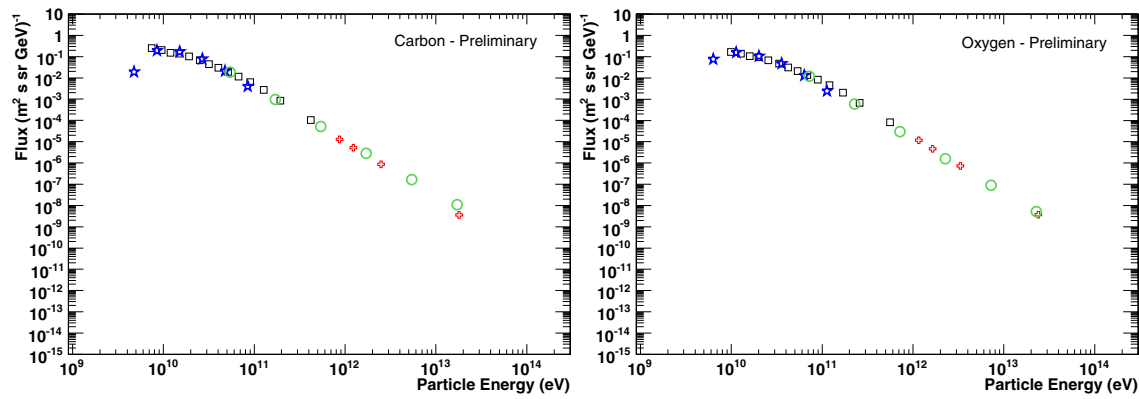


Figure 3: Preliminary cosmic ray energy spectra, measured with the CREAM Hi-Z system. The left panel shows the spectrum for cosmic Carbon nuclei; the right panel shows the spectrum for Oxygen nuclei. In both panels, the black squares represent data collected by the HEAO experiment ([2]), and the red crosses are from the CRN experiment ([7]). The blue stars and green circles represent events with energies reconstructed by the CREAM Cerenkov and TRD detectors, respectively. The normalization of the CREAM points have been adjusted with a single overall parameter applied in both panels and both detector results.

of the CREAM-I flight ( $\sim 30 \text{ m}^2 \text{ sr days}$  after initial cuts) was sufficient to collect abundant primary nuclei (*e.g.*, C & O) up to energies nearly twenty times higher than this. However, as can be seen on Figure 2, the energy range above  $\sim 1 \text{ TeV/nuc}$  (Lorentz factor  $\sim 1000$ ) corresponds to the region where the TRD detector response is dominated by the contributions of transition radiation processes. As a result of this shift, the TRD response and signal resolution in this region must be very well understood in order to properly deconvolve the measured spectra. Cross calibration from the CREAM calorimeter should help in this regard, and this work is underway. Once completed, we expect measurements of Oxygen nuclei to extend up to  $\sim 3 \times 10^{14} \text{ eV}$  total energy, and anticipate extending current measurement of the B/C ratio to  $\sim 500 \text{ GeV/nuc}$ .

## 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. Following this work, results on the fluxes of cosmic nuclei from Boron to Iron, over three decades in energy will be presented.

## References

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