Cosmic Ray Energetics And Mass (CREAM): A Detector for Cosmic Rays near the Knee

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Abstract

The Cosmic Ray Energetics And Mass Experiment (CREAM) is an experiment for ultralong duration balloon flights for measurements of cosmic rays in the energy region near the knee. CREAM will employ a combination of thin calorimetry, scintillation counters, and transition radiation detection to determine the energy spectrum and composition of the cosmic rays. In this paper, we focus on the technical approaches under study for the experiment, particularly for the measurement of charge of incident primary in the presence of albedo shower particles from the calorimeter. A novel approach to eliminating albedo from the charge measurement using fast timing techniques will be described. GEANT simulations are used to illustrate this technique, and plans for its development are discussed. An accompanying paper at this conference discusses the overall project goals in more detail (Seo et al. 1999).

1 The CREAM Instrument

The CREAM instrument (Figure 1) employs a scintillator-based charge detector, a transition radiation detector, and a thin calorimeter to measure the charge and energy of high energy cosmic rays. The charge detector must measure the charge of the incident particle while rejecting the copious albedo produced by the calorimeter. The calorimeter has an effective collecting aperture of ~ 0.35 m^2 sr for particles which pass through the charge detector. The transition radiation detector (TRD) measures the Lorentz factor for nuclei of Z$\geq$ 3 by determining the yield of transition x-radiation using thin gas detectors. Since the TRD provides a non-destructive measurement of the particle energy, events measured by the TRD can also be detected in the calorimeter. This unique combination of detectors allows a nucleus with a Lorentz factor determined by the TRD to produce a calorimeter response. Since there are no terrestrial sources of particles at 10^{14}eV this provides a direct calibration of the calorimeter for a subset of nuclei into an energy region which is inaccessible by accelerators. Until now this response has been determined only by simulations which are derived from lower energy results.

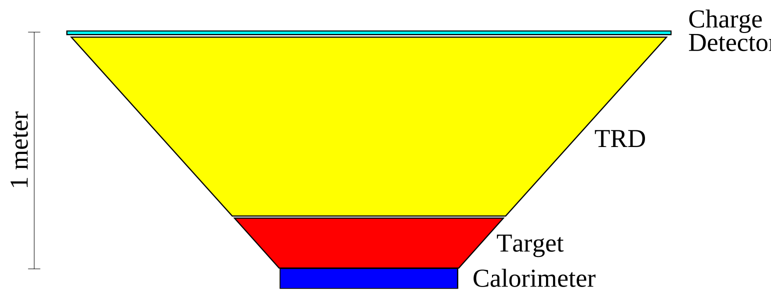

Figure 1: A schematic view of the CREAM detector configuration. Longitudinal segmentation of the major detector subsystems and additional scintillators interleaved with these detectors have been omitted for clarity.

2 Instrument Design - Calorimeter

Thin calorimetry has provided much of the direct measurements of the energy spectra of cosmic ray nuclei at high energy (see e.g. Shibata, 1996). It remains the only demonstrated method for the measurement of protons and helium above ∼1 TeV. For the scientific goals of CREAM a crucial role is played by the calorimeter. The overall calorimetry section shown in Figure 1 consists of a target section made of carbon (graphite) followed by a tungsten/scintillator layered calorimeter. This configuration is chosen since it maximizes the collection efficiency for hadrons for a calorimeter of a given mass.

The target section has a thickness of 0.5 proton interaction lengths which promotes hadronic interactions within this volume. Since the target is only 1 radiation length deep, the electromagnetic component of the shower can readily escape into the calorimeter. The calorimeter largely responds to the electromagnetic energy produced by these interacting particles. This consists of 20 radiation lengths of tungsten interleaved with a scintillating strip readout system which gives an energy resolution for vertical protons of $\sim$45%. The scintillating strips are used not only to fit the total shower energy but also to provide some tracking for the direction of the incoming particle. When combined with a segmented charge detector upstream, this tracking can be used to associate the event with a particular hit in the charge detector.

A major issue with calorimeter measurements is the accurate determination of the incoming particle charge. At high energy albedo particles from the shower interactions can arrive at the charge detector and provide additional ionization loss signals. For light nuclei this effect can produce the misidentification of some protons as helium nuclei. Since the shower albedo increases with particle energy the fraction of misidentified protons is likely to increase at high energies. Spatial segmentation in the charge layer can be combined with the tracking provided by the calorimeter to help with this issue but ultimately the density of albedo particles in the charge layer could make the number of channels required unacceptably large. A new solution to this problem is discussed in Section 4.

3 Instrument Design - Transition Radiation Detector

The TRD consists of plastic fiber radiators combined with thin-walled proportional tube detectors filled with a xenon gas mixture. This design has the advantage of not requiring a pressure vessel which significantly reduces the weight of the assembly, important for the stringent weight limits of ultra long duration balloon payloads. The particles passing through the radiators produce transition radiation x-rays at energies near 10keV. Since this is a purely electromagnetic effect the response can be calibrated using high Lorentz factor charged particles at accelerators. These can be easily scaled, using Z^2, to determine the mean response for heavy nuclei. The multiple measurements made by TRDs allow a good determination of the measurement fluctuations from the flight events themselves. Accurate knowledge of the details of these fluctuation distributions are vital to deconvolve the steeply falling cosmic ray spectrum from the measurements.

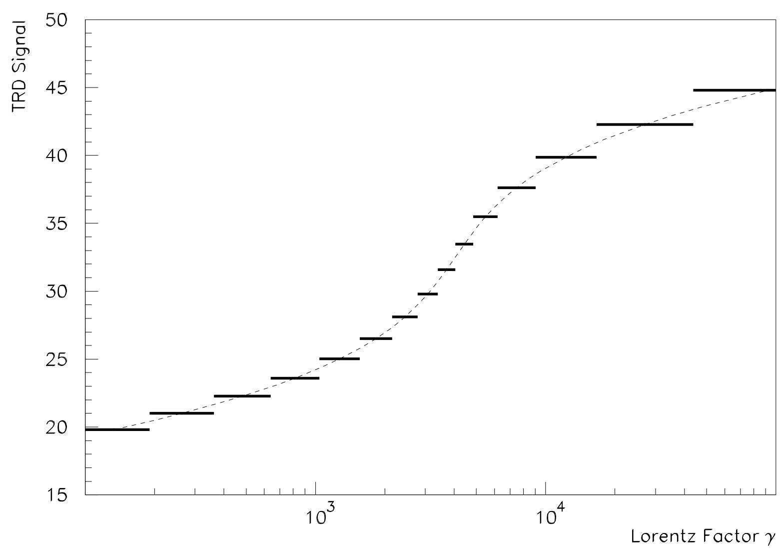

Figure 2: The simulated response of a TRD for CREAM. The dashed line represents the mean response versus particle Lorentz factor. The thick horizontal lines show an example the expected overall energy bins available from this detector from the passage of a single Carbon (Z=6) nucleus. The rms fluctuation in signal width is essentially constant throughout the range hence the width of these bins is dominated by the slope of the response curve.

Since CREAM is aimed primarily at particles with Lorentz factors above 10^3, the response of the TRD must be tuned to lie in this range by a suitable choice of radiator material and detector thickness. Previous TRDs developed for elemental spectra measurements have provided a response at somewhat lower Lorentz factors (Swordy et al. 1982). For this instrument polyolefin fiber radiators with fiber diameters of ~50μm mean spacings of ~500μm are used. When combined with xenon filled detector tubes the expected response of this assembly is simulated in Figure 2. Here the horizontal bars represent the width of energy bins provided by this TRD which could be achieved for carbon (Z=6) nuclei. The response extends to a Lorentz factor of $\sim 3 \times 10^4$ or $\sim 4 \times 10^{14}$eV total energy for a carbon nucleus.

4 Charge Identification Using a Time-Resolved Technique

As mentioned, the identification of the incident particle charge is hampered by albedo from the calorimeter. The conventional method of preventing misidentification of the incoming particle involves fine segmentation of the charge detector, and precise tracking in the calorimeter to allow extrapolation of the shower axis to the charge detector (see e.g. Guzik et al. 1996). This scheme has several drawbacks. Fine segmentation requires a high channel count, and edge effects in the detector segments can potentially degrade the charge resolution. In addition, the need for fine tracking often drives the design of the calorimeter.

An alternative approach takes advantage of the fact that the incident particle traverses the charge detector *before* impacting the calorimeter, and that the albedo returns to the charge detector several nanoseconds later. Plastic scintillation counters with excellent time response can be easily fabricated to cover large areas. A detector consists of a long thin slab of scintillator with adiabatic lightpipes at each end which match the scintillator to two fast photomultipliers. The width of the scintillator is chosen to match the area of the end of the scintillator to the active area of the photomultiplier. Such detectors are frequently used to measure charge and velocity in cosmic ray experiments. Light propagates along the scintillator at an effective velocity of $\sim 0.6c$, and the incident particle and most albedo particles travel at c. A simple geometrical analysis shows that light from the incident particle will arrive at at least one of the photomultipliers prior to the light from any albedo particle.

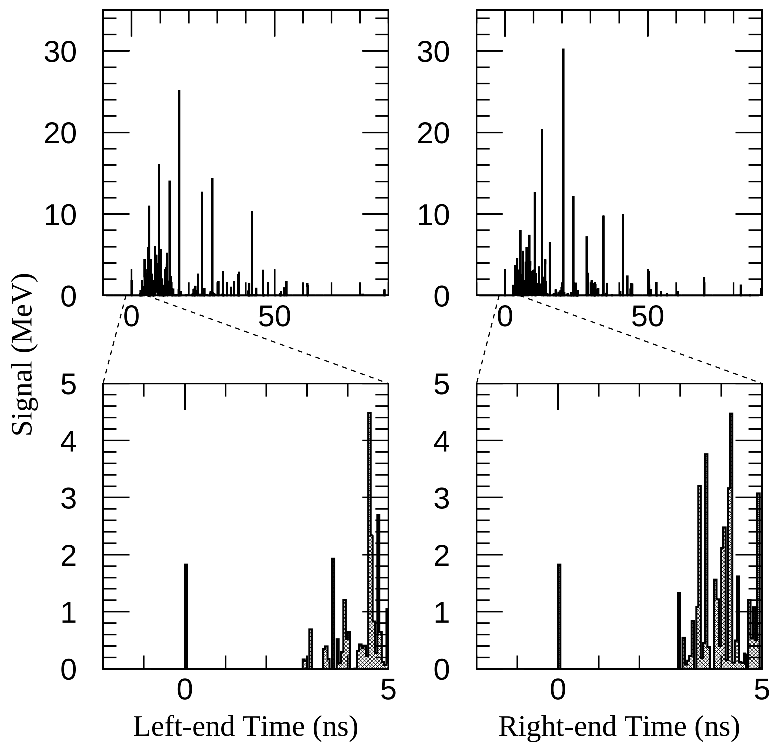

Figure 3: A GEANT simulation of the signals in the charge detector PMTs for a vertical 99 TeV proton impacting at the center of the CREAM instrument. The incident particle signal appears at time zero in both PMTs. The region near this time is expanded in the lower panels, showing the $\sim$ 3 ns time prior to the arrival of light from the first albedo particle. Optical and electronic time dispersion effects have not been included in the simulation.

The GEANT3 simulation package was used to simulate the time of arrival of photons at the photomultiplier. A sample event is shown in Figure 3. A $2\text{m} \times 2\text{m} \times 1\text{cm}$ scintillator 1 m above the calorimeter was studied. All detectors from the baseline configuration were included in the simulated detector. The FLUKA hadronic interaction package was used. Scintillation photons are propagated along the scintillator at the effective velocity, and attenuation of light in the scintilator is treated. Signals are normalized to give accurate energy deposits at the center of the detector. The effects of scintillator saturation and of optical and electronic time dispersion are not included. All particles impacting the 2 m $\times$ 2m detector are shown; segmented readout will reduce the amount of albedo appearing with the incident particle.

The case shown is the worst case, a vertically incident particle at the center of the detector. Inclined tracks can result in one or the other of the PMTs receiving a signal from an albedo particle prior to the arrival of the incident particle signal, but in all cases at least one PMT will contain a signal from the incident particle preceeding the albedo by several nanoseconds. Timing and tracking information from the calorimeter may be used together with the timing pattern in the charge detector photomultipliers to identify which photomultipliers contain an albedo-free signal. Further simulation studies are underway to study the performance required for accurate event reconstruction.

Several technical challenges must be overcome to make a time-resolved charge detector practical. Sources of time dispersion in the production of the scintillator signal and its detection and digitization must be minimized. Based on the properties of the Bicron BC-408 scintillator and a typical fast photomultiplier response, we estimate that over half of the signal from the incident particle will arrive within a 2-3 ns period. The signal arriving during this interval could be determined using either a fast waveform digitizer or by employing a self-triggering gated integrator built using GaAs switches to obtain the early part of the signal uncontaminated by albedo.

5 Summary

The detectors for CREAM are at present under study with development expected to start in late 1999. We expect CREAM to be qualitatively different from other balloon experiments to measure high energy composition. Apart from the engineering challenge to make the payload function unattended for $\sim$100 days, more sophisticated approaches to thermal control, mechanical design, and data recovery are required than for conventional balloon payloads. The two key instrumentation advances of CREAM are the combination of the TRD and calorimetry in a single experiment, and the introduction of fast timing to reject calorimeter albedo.

References

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