An ULDB Mission to Study High Energy Cosmic Rays

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Abstract

Scientific ballooning technology will soon allow flights of about 100 days at altitudes in excess of 110,000 feet. Utilizing these Ultra Long Duration Balloon (ULDB) flights, the Cosmic Ray Energetics And Mass (CREAM) project will measure the energy spectra and elemental abundances of H to Fe over the energy range 1 to 1000 TeV. The goal is to observe spectral features and/or abundance changes that might be related to a supernova acceleration limit. The CREAM instrument will consist of a sampling tungsten calorimeter preceded by a carbon target with scintillator layers for trigger and track-reconstruction purposes, a transition radiation detector (TRD) for heavy nuclei, and a segmented scintillator-based charge detector. In this paper, we focus on an overview of the project, while an accompanying paper at this conference (Beatty et al., 1999) will discuss some technical aspects. A key feature of this instrument is the measurement of the energy of a subset of nuclei by complementary techniques, which can be used to intercalibrate the energy scales of the TRD and calorimeter.

1 The CREAM Mission:

Cosmic-ray elemental composition has been measured by space-based experiments that determine the incident particle charge as well as its energy. However, the composition above 1 TeV is not very well known due to limited exposures for such experiments. Indirect measurements from ground-based experiments have traced the all-particle spectrum from about 10^{14} eV to > 10^{20} eV. These measurements have shown that the energy spectrum above 10^{16} eV is somewhat steeper than the spectrum below 10^{14}eV. An explanation for this change in spectral shape, the spectral “knee,” is one of the major current goals in cosmic-ray astrophysics. Acceleration of cosmic rays in supernovae remnants is expected to be limited at energies near Z x 10^{14} eV, where Z is the particle charge (Lagage & Cesarsky, 1983). This implies that the composition would begin to change beyond energies of about 10^{14} eV. A search for changes of the elemental composition in the decade above 10^{14} eV could reveal this supernova acceleration limit.

As shown in Fig. 1, CREAM consists of a particle charge detector at the top, followed by a TRD, a target for nuclear interactions, and a calorimeter to measure the interaction products, thereby giving particle energy estimates. A large exposure can be accumulated in a series of ULDB flights of identical instruments. The different flights could be carried out at essentially any latitude, including the polar regions, in either the Northern or Southern hemisphere. The overall CREAM objective is to accumulate at least 500 particles each for protons, helium, CNO, Ne-Si, and Fe

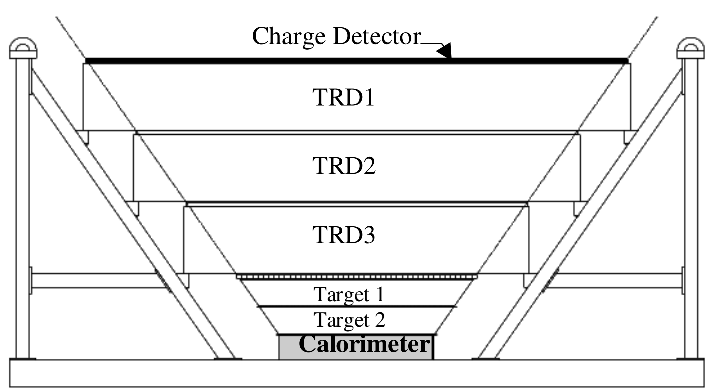

Figure 1: CREAM Baseline Configuration.

group nuclei above 10^{14} eV, with a statistical accuracy of 30% above 10^{15} eV. This requires an exposure of about 300 m^2-sr-days for protons and helium nuclei and about 600 m^2-sr-days for heavy nuclei (Waddington et al., 1992).

The instrument is being optimized for a low-cost, integrated balloon craft capable of providing the required energy and charge resolution. We expect to begin development of the instrument in late 1999, in order to be ready for a single-day flight in May 2002, followed by a ULDB flight.

2 CREAM Measurement Techniques:

CREAM is fundamentally different from other high energy composition experiments in that it employs both TRD and calorimeter devices in the same payload. While both of these types of detector have been flown before for high energy composition measurements, the combination of instruments provide a powerful method to overcome the individual shortcomings of each technique. A subset of nuclei will provide a response in both detectors that can be used to calibrate the calorimeter energy scale against the TRD. Also the calorimeter can detect protons and He which the TRD can not reliably determine the energy.

Additionally, the charge-determining detectors must be protected from the effects of backsplash particles produced in the calorimeter shower. For CREAM this is accomplished partially by detector segmentation but largely by a time of flight technique which can reject albedo particles from the calorimeter. This approach is discussed in an accompanying paper (Beatty et al., 1999).

CREAM will provide a substantial overlap in energy with ground-based composition experiments, which have thresholds near 10^{14} eV (Amenomori et al., 1996). This provides an important cross-calibration with the ground-based data. Ground-based detectors observe the extensive showers of secondary particles initiated when a primary cosmic ray interacts with a nucleus of the upper atmosphere.

The interpretation of air shower measurements depends on assumptions regarding the nature of the particles that initiate the showers. Showers from heavier nuclei typically start higher in the atmosphere and develop more rapidly than showers from lighter nuclei. Estimates of the primary composition depend on parameters such as the depth of the shower maximum in the atmosphere and several other shower parameters, e.g., muon content. Energy estimates are affected by the assumed composition of the primary particles. Direct measurements from CREAM will allow prediction of cascade models of air shower parameters to be directly compared with a known primary composition. This will provide confidence for extending direct composition measurements to higher energies.

3 Instrument Configuration:

There is no practical alternative to a calorimeter for measuring protons and helium energies up to 10^{15} eV. To illustrate the calorimeter configuration and the type of data it will collect, we show in Fig. 2 the shower associated with a single, simulated 10^{12} eV proton event. To optimize the use of available weight, a hadronic calorimeter can be made by adding a light target material, such as carbon, upstream of an electromagnetic calorimeter (Ganel, Seo, & Wang, 1999). A large dynamic range is needed to allow measurement of energies over a wide range. Fine granularity will allow improved tracking information.

The geometry factor of the calorimeter must be maximized to collect statistics. Given the fixed mass limit of ULDB payloads, currently 1000 kg, this requirement can be realized with dense materials (e.g., W

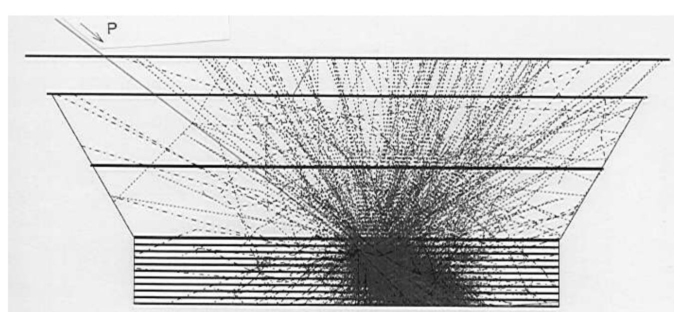

Figure 2: Simulated 1 TeV proton shower in the CREAM calorimeter.

or U) where the physical depth of the calorimeter can be substantially less than 10 cm for an acceptable depth of at least 20 radiation lengths (X_0). Either C or Be is needed to maximize the number of interactions in the target. Carbon is used as a target material since it is readily available, easy to machine and handle (Ganel, Seo, & Wang, 1999). CREAM is baselined with a 0.5 λ_{int} carbon target and a 20 X_0 deep W/Sci calorimeter. Taking into account the actual pathlength through the instrument, the effective geometry factor for the calorimeter is 0.35 m^2-sr for protons entering the top of the target and having at least 20 X_0 for shower development in the calorimeter. The payload would have to fly about 860 days to achieve 300 m^2-sr-days effective exposure for protons. About 3 ULDB flights would provide 100 m^2-sr-days to reach about 500 TeV. For a mass limit of 1500 kg, the effective geometry factor would increase to 0.57 m^2-sr and the corresponding required flight time to reach 1000 TeV would be reduced to 530 days.

The effective exposure of the calorimeter for heavier nuclei is greater than for protons due to their shorter interaction mean free path in the carbon target, which scales as about $A^{2/3}$, where A is the atomic mass of the projectile nucleus. Using this scaling law, the exposure for heavier projectiles can be estimated from the proton interaction length. The effective geometry factor for heavy nuclei is 0.57 to 0.7 m^2-sr, and exposure factors for these nuclei corresponding to the 860 and 530 day flights required to reach our goal for protons are about 500 – 600 m^2-sr-days. The effective geometry factor for events traversing the full instrument from the charge detector through the TRD to the calorimeter and not interacting in the TRD but interacting in the target is about 70% of the calorimeter-only geometry factor discussed above. Events meeting this criterion can be used for a cross calibration of the TRD and calorimeter. The energy resolution of the calorimeter for vertically incident protons is about 45% as shown in Fig. 3, and it does not vary much with energy. The actual resolution is better than the number quoted here because the average pathlength of isotropically incident particles in the instrument is longer. Note that the heavy ion energy resolution is much better than that for protons (Seo et al. 1996).

The TRD has 6 radiator-detector pairs that cover the full geometry of the target plus calorimeter. The radiators consist of 12 cm thick inhomogeneous, light-weight material (e.g., synthetic fibers). Each detector is a double layer of 2 cm diameter cylindrical single-wire, xenon-filled proportional tubes with thin (~ 75 micron) walls of aluminized Mylar, which function with zero external pressure. Similar tubes are being used in the TRACER (Transition Radiation Array for Cosmic Energetic Radiation) payload being developed for LDB flights (Muller et al., 1996). The signals produced by nuclei traversing the detector tubes can be used to determine both the Lorentz factor ($\gamma = E/mc^2$) and the trajectory of the particle through the instrument. The TRD will be used to measure $Z \geq 3$ nuclei with an energy resolution of 15% for carbon and 7% for iron at $\gamma = 3000$. Importantly, the energy response of the TRD can be calibrated at a test beam.

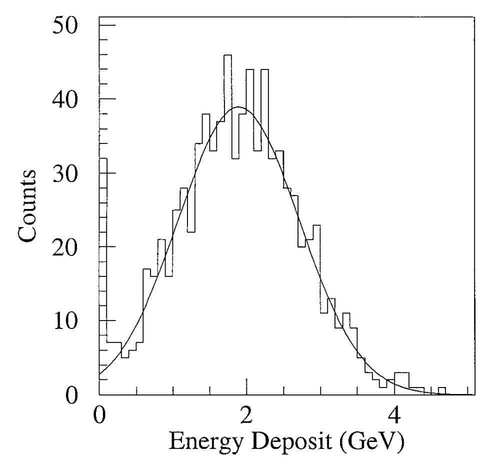

Figure 3: Simulated energy deposit in the W-Sci calorimeter for vertically incident 1 TeV protons.

4 Measurement Capabilities:

The CREAM measurements will be able to verify whether the proton and helium spectral differences that have been reported (e.g., Ellison et al., 1994) from combining all the existing data sets are indeed real. Since the existing data were collected with several types of detectors, including several different designs of emulsion chambers, some of the spread in the data is undoubtedly due to systematic errors and differences in normalization among experiments. Nevertheless, taking the data at face value, the proton and helium spectra appear to be different at high energies (> 100 GeV/n), while helium has the same spectral shape as heavier nuclei. This unexpected finding has received considerable attention, because simple shock acceleration theory predicts the same power-law rigidity spectra for all species. To illustrate the effectiveness of CREAM to detect a change in the proton spectrum, Fig. 4 shows the maximum kink energy that can be clearly observed as a function of flight time for both the 1000 kg and 1500 kg reference payloads. The curves are for a 2σ significance level for two integral spectral indices, γ_2 = 2.0 and 2.2, above the kink, where the index below the kink is γ_1 is 1.7, i.e., for index changes of 0.3 and 0.5 at the kink (Sina & Seo, 1998).

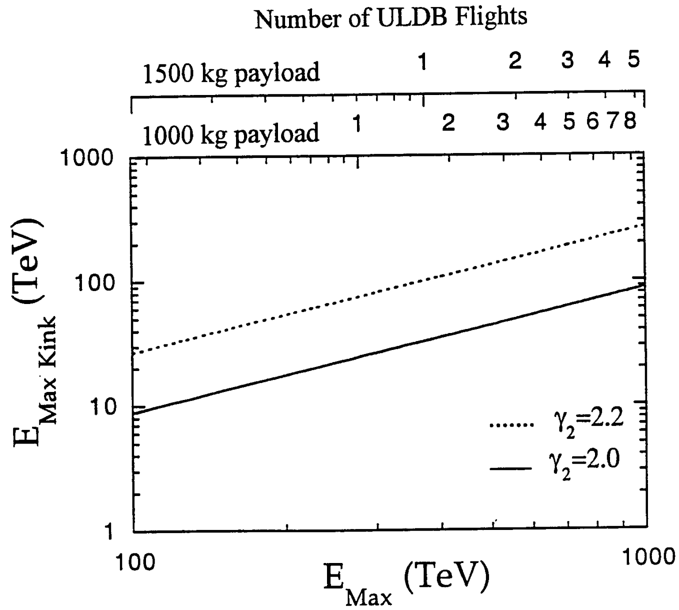

Figure 4: Maximum kink energy that can be observed by CREAM as a function of flight time assuming 100 days of exposure per flight.

The individual charge resolution and energy response of CREAM also allows a sensitive measurement of secondary nuclei produced in the interstellar medium. At present these measurements extend to around 100 GeV/n. It seems unlikely that the energy dependent decrease in propagation pathlength will extend to the "knee" region since the residual pathlength at these energies would be uncomfortably small. CREAM can search for a change in the energy dependence out to ~ 1 TeV/n, an order of magnitude above present data.

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