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Timing charge and position analysis from the first CREAM flight

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Abstract: The Cosmic Ray Energetics And Mass (CREAM) experiment is a program of cosmic ray studies flown on NASA Long Duration Balloons (LDB) launched from McMurdo Station, Antarctica. The analysis presented here uses data from the first CREAM flight which lasted a record breaking 42 days in the 2004/2005 season. The timing analysis of the Timing Charge Detector (TCD) will be discussed in this paper. This includes charge reconstruction from the rise-time of the scintillation signal in the presence of albedo due to the TCD's proximity to a target. Position extraction utilizing the fast timing electronics of the TCD is also presented.

Introduction

The CREAM experiment's goal is to measure the differential cosmic ray (CR) energy spectrum from 10^{12}eV to 10^{15}eV for elements up to iron. This measurement will help understand CR acceleration in supernova remnant shocks and the process of CR propagation in the Galaxy through elemental composition. The first CREAM payload flew for a record-breaking 42 days in the 2004/2005 season from McMurdo Station, Antarctica. This payload was composed of a TCD, a Transition Radiation Detector (TRD), a Cherenkov Detector (CD), a Silicon Charge Detector (SCD), scintillating hodoscopes, and a tungsten sampling Calorimeter (CAL). The CREAM instrument has been described in detail elsewhere [1]. A similar flight of 28 days was made in the 2005/2006 season with a slightly different instrument; for details about this second flight see [2]. TCD data from the first flight will be the focus of this analysis, but the analysis method is equally relevant to data from the second flight since the TCD was identically constructed.

Timing Charge Analysis

The TCD is composed of 2 layers of 4 thin plastic scintillating paddles, each $30\mathrm{cm} \times 120\mathrm{cm} \times 0.5\mathrm{cm}$.

The layers are oriented orthogonally to one another as shown in Fig. 1. At the end of each paddle, an adiabatic light pipe transitions the rectangular geometry of the paddle to the circular photocathode of a PMT. Each end of the paddle is read out by 2 PMTs, for a total of 16. The goal of the TCD is to measure particle charge such that individual elements can be resolved from protons up to iron. To measure charge, a peak-finding board is used which measures the peak of the scintillation signal from the CR. However, with a dense CAL sitting $\sim 1\mathrm{m}$ below the TCD, this measurement is complicated due to the back splash, or albedo, created when a high energy CR interacts in the CAL. The albedo is composed mainly of neutral particles, but there is a charged component of mainly $Z = 1$ that can cause charge misidentification in the TCD, particularly for similarly charged CRs [3, 1].

There are two methods of dealing with this albedo, each having its own strengths and weaknesses. Most experiments use a segmented detector, which isolates the CR to a single channel. The SCD, positioned directly above the CAL, is an example of this. By reducing pixel size, the CR can be picked out from the albedo; however, it requires a detector with many channels, which would translate into a large increase in power for a detector like the TCD. For a balloon experiment, power and data storage are limited and therefore the TCD uses a second method which requires fewer channels. This involves taking advantage of the detector geometry. The TCD sits $\sim 1\mathrm{m}$ above the CAL, which corresponds to a minimum separation of $\sim 3\mathrm{ns}$ between the CR and albedo signals. The TCD utilizes fast electronics in order to measure the rise-time of the signal at the PMT, avoiding the albedo signal that follows. For more about a Monte Carlo simulation of this time delay see [3].

The peak finding technique works well for $Z \geq 3$ because the signal is much larger than the signal from albedo. However, for protons and helium this becomes a large source of charge misidentification. It is possible for the peak from the albedo to be larger than that of the CR due to pile up of multiple albedo particles. This results in the peak detectors measuring the albedo peak. Instead of relying on the peak, two Time-to-Digital Converters (TDC) are used to measure the rise-time of the PMT signal. For each TDC, a voltage comparator triggers the TDC when the incoming signal is greater than a set threshold. Since the TDCs are operated in a common stop mode, the difference of the two TDC times is a measure of the time taken by the PMT signal to rise from the lower voltage threshold to the higher threshold. This produces an effective rise-time, $\Delta t_r = \mathrm{TDC}[x][1] - \mathrm{TDC}[x][0]$, where $\mathrm{TDC}[x][y]$ refers to the TDC value on tube x for threshold y. The rise-time is inversely proportional to the peak of the signal, which is proportional to the square of the charge. Thus, the rise-time provides another charge measurement while avoiding the noise that follows from the albedo [3].

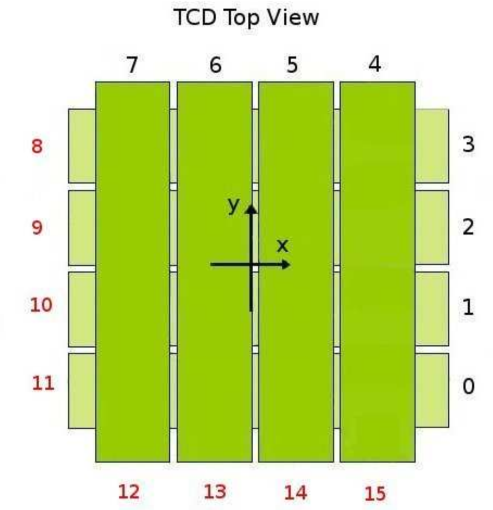

Figure 1: TCD Geometry including axis definitions. There are PMTs at both ends of each paddle. The PMT numbers are 0-15; the paddle numbers are 0-7.

The rise-time charge identification is useful for $Z \leq 5$ because the charge distributions quickly overlap due to the inverse proportionality, as shown in Fig. 2. This plot was made using a GEANT simulation of a single TCD paddle and shows the expected rise-time for protons, helium, lithium, carbon, and oxygen as measured by thresholds 0 and 1 in one of the PMTs (for more on this GEANT simulation see [4]). Figure 2 shows the close proximity of the distributions of nuclei; only protons can be fully separated, with He/Li and C/O each overlapping. Due to the lack of lithium flux, the helium peak can still be extracted from this plot.

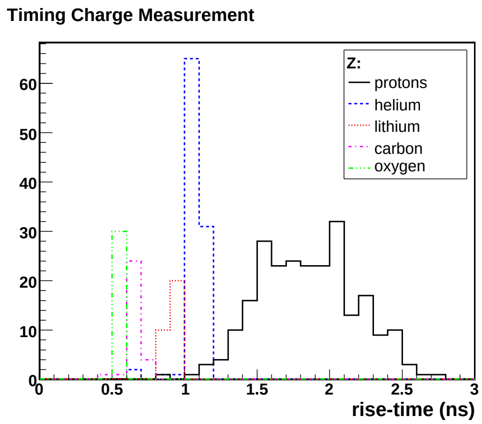

Figure 2: Histogram of the rise-time measurement from a GEANT simulation of a single TCD paddle. This rise-time is inversely proportional to charge. Here p, He, Li, C and O can be seen to follow this inverse proportionality. However, only the distribution of protons can be confidently separated.

Thresholds 0 and 1 look at the PMT signal on the anode and there is another set, thresholds 2 and 3, which look at the 11^{th} dynode (there are 12 dynodes per PMT). These additional thresholds see the PMT signal at a lower gain level and were set such that the Li, Be, and B can be measured.

Before extracting Δt_r from the TDCs in the TCD, one must first calculate the constant time offsets for each threshold on each PMT, which are caused by differing signal cable lengths and electronics delays. Once these offsets are removed, all TDCs will refer to the same time scale. This requires plotting each TDC versus the CR hit position in the paddle and making a linear fit. The constant from this fit is the offset. This process is explained in more detail in [5].

Current analysis has shown that albedo rejection is crucial for rise-time charge identification. Due to the similar charge of albedo to the incident protons and helium, it is necessary to utilize the event's geometry. Within the TCD, a CR incident near the end of a paddle should produce a signal in the nearby PMT with the appropriate rise time. However, the signal measured at the opposite end of the paddle, due to attenuation, will be smaller and more susceptible to charge misidentification due to incident albedo particles. The near end should still provide an accurate measure of the rise-time and thus a measure of the charge, even in the case of albedo. Utilizing the position measurements within the TCD, the CAL, and the SCD, one can determine the appropriate PMT signal to use in the rise-time measurement. There is also contamination due to events triggered solely by albedo events. These events can be removed by requiring that the particle track in the detector be downward going. This rejection process is on-going and must be developed further before a charge measurement can be extracted from the timing.

Timing Position Measurement

The position of the incident CR is determined from the difference in the times, Δt_x, measured in the PMTs at opposite ends of a paddle. This Δt_x is proportional to $\frac{x}{v}$ where x is the distance to the paddle end from the CR impact point and v is the velocity of light in the scintillator.

In order to relate Δt_x to the incident CR's position in the paddle, one can histogram Δt_x with the event by event requirement that one and only one paddle in the orthogonal direction measured a signal. For instance, one could histogram Δt_x in paddle 1 four separate times with each plot corresponding to events where only paddle 4, 5, 6, or 7 had PMTs with data. This is shown in Fig. 3, where four distinct distributions can be seen, corresponding to the four crossing paddles.

Then, for each distribution a mean time can be determined, which corresponds to a known midpoint of the crossing paddle. This provides four points of the mean Δt_x versus the mean x position in the paddle. These points allow a linear fit that can be used to determine the position of impact for the CR based on Δt_x.

To verify the accuracy of this method, one can plot the difference in the position derived from both the TRD and the TCD (the TRD position is known to be accurate on the mm scale [6]). Such a plot produces a Gaussian distribution with a position resolution of $\sigma = 3.49\text{cm}$. This corresponds to a time resolution of about 175ps.

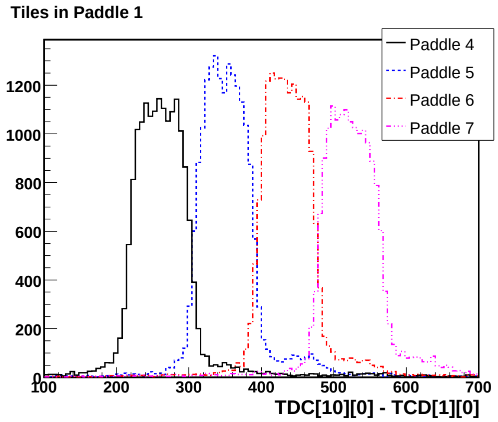

Figure 3: Histogram of the difference in TDC values from PMTs at opposite ends of paddle 1.

Conclusion

The TCD performed well in its maiden flight, operating with an excellent timing resolution of $\sim 0.2\mathrm{ns}$. The timing charge analysis is ongoing with the goal of resolving the individual charge peaks for $Z \leq 5$. The albedo rejection technique is being improved in order to reach this goal. Future analysis with the TCD paddle simulation will include the appropriate CAL module, which should provide insight into new ways of rejecting albedo. Since all flights utilize identical TCDs, the two analyses presented here are equally applicable to all CREAM flights.

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