Precise Identification of Heavy Cosmic-Ray Nuclei: The Role of Delta Rays

F. Gahbauer, G. Hermann[1], J. Hörandel[2], D. Müller, and A. A. Radu [3]
The Enrico Fermi Institute, The University of Chicago, 933 E. 56th Street, Chicago, IL 60637, USA
(1) presently at Max Planck Institut für Kernphysik, Heidelberg
(2) presently at University of Karlsruhe, Germany
(3) presently at Institute for Space Sciences, Bucharest

Abstract

Relativistic δ rays may lead to detector response functions, both in charge and energy, which are different from those expected for unaccompanied particles. These effects are particularly noticable for cosmic ray nuclei with large charge number, Z. We shall demonstrate some of these features with balloon-borne data obtained with the TRACER instrument, and compare the measurement with Monte Carlo calculations. Our results illustrate how δ-ray effects can lead to false charge assignments or acceptance efficiencies if not properly taken into account, but also how they can be helpful in extending the energy response of some of the counter elements.

1. Introduction

When a relativistic particle traverses a detector, such as a plastic scintillator or a Čerenkov counter, the recorded signal may have significant contributions due to δ rays. These either are produced by the particle in the detector material, or may accompany the particle but have been generated before the particle entered the detector. The energy dependence of the signal contributions due to δ rays may be different from that of signals due to particles unaccompanied by δ rays. This feature is difficult to determine for singly charged particles because of the long tails of signal distributions, but it does become apparent for the much narrower distributions at higher Z and must be taken into account in the analysis of the measurement.

We discuss these effects for the TRACER instrument, which is a balloon-borne detector built to measure the intensities of the heavier nuclear species in the cosmic rays up to energies of 10 TeV/nucleon (see Müller et al, this conference). It includes two plastic scintillators to trigger the instrument and to measure the charge of each particle. These are located at the top and at the bottom of the instrument, respectively, and thus permit rejection of nuclei that may have inter-

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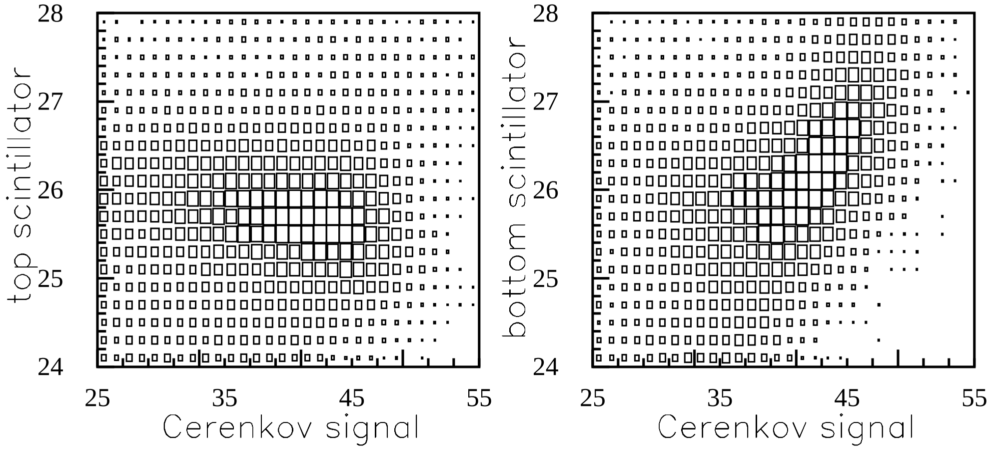

Fig. 1. Scintillator signals versus Čerenkov signals for iron flight data.

acted in the detector. Also at the bottom of the instrument is an acrylic Čerenkov counter to reject low-energy particles. The bulk of the TRACER instrument between the two scintillators consists of arrays of single-wire proportional tubes that either measure the specific ionization in gas or also detect superimposed signals from transition radiation x-rays that are generated in plastic fiber radiators. Each of the detector elements has a characteristic but different energy response, and the correlation of signals for each cosmic-ray particle leads to a measurement of its energy.

2. Observations

The scintillation counter signals serve as an energy-independent means of measuring the particle charge, Z above minimum ionization. Towards lower energies, the scintillator signals increase while the Čerenkov counter signals decrease. Thus, a scatterplot of a scintillator signal versus the Čerenkov signal easily identifies those particles whose energy is below minimum ionization and allows them to be rejected. The flight data, however, reveal a more complex situation. Figure 1 shows scatterplots of the signals from the two scintillators versus the Čerenkov signal for iron nuclei. Two different correlations are apparent. The slight decrease in the top scintillator signal with increasing Čerenkov signal reveals that some of the particles that have been observed are below minimum ionization. Beyond minimum ionization, the top scintillator signal does not vary significantly with energy. The situation is quite different, however, for the bottom scintillator. This signal exhibits an increase with increasing Čerenkov signal. When the Čerenkov

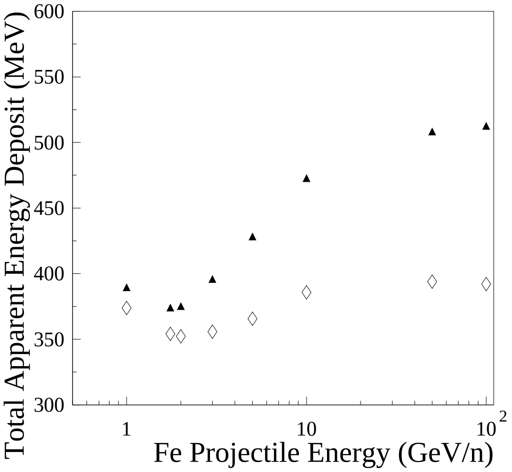

Fig. 2. Scintillator energy deposit.

top scintillator (open diamonds);
bottom scintillator (filled triangles)

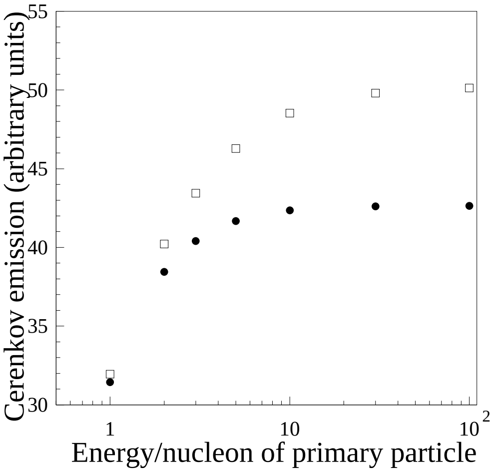

Fig. 3. Čerenkov light yield.

Čerenkov counter without δ rays (filled circles); with δ rays (open squares)

signal reaches saturation, the bottom scintillator signal indicates an apparent charge that is greater than that of iron by almost one charge unit.

3. Monte Carlo Studies and Interpretation

These effects can be explained quantitatively by the production of penetrating δ rays. There is relatively little material to produce δ rays upstream of the top scintillator, but the material between the two scintillators generates a number of δ rays with sufficient energy to reach the bottom of the detector. The number of penetrating δ rays increases with primary particle energy up to about 10 GeV/n, but reaches saturation between 10 and 100 GeV/n. The δ rays generate a significant fraction of the total energy deposited in the bottom scintillator. This is qualitatively investigated in a Monte Carlo simulation.

The simulation generates δ rays along the primary particle's trajectory, which are tracked until they either stop or leave the instrument. The energy they deposit in the scintillators and the Čerenkov light they generate are recorded. Figure 2 illustrates the results of this calculation for the two scintillators. Shown is the total *apparent* energy deposit from both δ rays and primary ionization. Note that the δ rays are weighted more heavily in the total *apparent* energy deposit than the *actual* energy deposits would indicate. This is due to the fact that the conversion of deposited energy to light becomes nonlinear along the track of a heavily ionizing primary particle with $Z > \ \sim 10$. The δ rays, on the other hand,

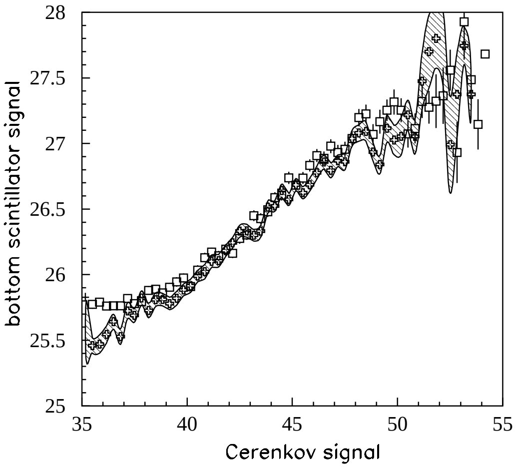

Fig. 4. Average scintillator signal as a function of Čerenkov signal.

simulation (boxes) and flight data (crosses) for iron

are spatially separated from the primary trajectory and singly charged, so their energy deposit is more efficiently converted into light. Figure 3 shows the results of the Monte Carlo calculation for the Čerenkov counter. The figure shows the calculated Čerenkov yield with and without taking δ rays into account.

A surprising but quite desirable feature of the δ-ray contribution is that it extends the region where the response of the acrylic Čerenkov counter increases with energy to beyond 10 GeV/nucleon, well beyond the saturation of a "pure" Čerenkov counter.

The results of the above studies are parametrized and fed into a GEANT 4 Monte Carlo of the entire detector. Random fluctuations consistent with real signal fluctuations are added to the simulated signals. Figure 4 shows the average scintillator signal in the bottom scintillator versus the Čerenkov signal. We notice excellent agreement between the simulation and the measured data in flight.

4. Conclusion

The Z^2 dependence of the electromagnetic energy loss processes allows precise measurements of the specific energy loss of heavy cosmic-ray nuclei. However, these gains in resolution for heavy nuclei uncover subtle energy dependencies that are hidden in the fluctuations for singly charged particles. If these effects are not carefully studied and understood, they can lead to false charge assignments or energy-dependent efficiencies. However, the effect of δ rays has also been found to be advantageous in TRACER as it extends the energy response of the Čerenkov counter and improves its low-energy discrimination ability.