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The Response of the TRACER Detector: Design, Calibrations and Measurements

C. Höppner[a], M. Ave[a], P. Boyle[a], F. Gahbauer[a], J. Hörandel[b],
M. Ichimura[c], D. Müller[a], A. Romero-Wolf[a] and S. Wakely[a]

(a)Enrico FermiInstitute, University of Chicago, 5640 South Ellis Avenue, Chicago, IL,60637
(b) University of Karlsruhe, Germany
(c) Hirosaki University, Japan
Presenter: C. Höppner (hoppner@uchicago.edu), usa-hoeppner-C-abs1-og11-oral

TRACER ("Transition Radiation Array for Cosmic Energetic Radiation") is currently the largest detector system for direct measurements of cosmic-ray nuclei on balloons. The instrument combines arrays of single-wire proportional tubes for measurements of specific ionization and transition radiation with large-area plastic scintillators and acrylic Cherenkov counters. We shall describe the response functions of the individual detector elements, and the correlations between them which make possible an unambiguous identification of heavy cosmic-ray nuclei ($8 \leq Z \leq 26$) by charge Z and energy E or Lorentz factor $\gamma = E/mc^2$, covering an energy range of four decades.

1. Introduction

Measurements of the cosmic-ray composition to energies approaching the "knee" above 10^{15} eV have been a long-standing goal of cosmic-ray astrophysics. However, experimental progress has been slow because of the rapidly falling intensities which require observations with exposure factors of the order of at least several m^2 ster year for the nuclei heavier than helium. These are difficult if not impossible to accomplish on balloons with traditional instruments, but may be approached in repeated long-duration flights of systems that use transition radiation detectors (TRD) for energy measurements. As a step in this direction, the TRACER instrument has been developed and exposed successfully in a one-day test flight in 1999 [1], and in a 10-day Antarctic long-duration flight in 2003 [2]. The instrument has a geometric factor of 5 m^2 ster.

2. Description of the Detector

The TRACER concept is based on electromagnetic detection techniques. It achieves a large detector area-to-weight ratio because a nuclear interaction of the particle is not required. The instrument is composed of two plastic scintillation counters, an acrylic Cherenkov detector, and an array of 1600 single-wire proportional tubes. In its current configuration, TRACER is tuned for measurements of the heavier cosmic-ray nuclei, from oxygen (Z = 8) to iron (Z = 26).

A schematic drawing is shown in figure 1. The scintillators on top and at the bottom of the instrument measure the charge Z of the particles and also serve as trigger. The Cherenkov counter is sensitive to particles with energy above 0.5 GeV/amu and is used to identify low energy particles. The proportional tube array provides energy measurements for highly relativistic particles. It consists of two components: The upper half of the array measures the specific ionization signal ("proportional tube array" in figure 1 which serves as "dE/dx" detector). The lower half which is interspersed with transition radiator material (blankets of plastic fibers) measures specific ionization with X-ray transition radiation (TR) superimposed ("transition radiation detector" in the figure). The use of proportional tubes as ionization and X-ray detectors, rather than more conventional multi-

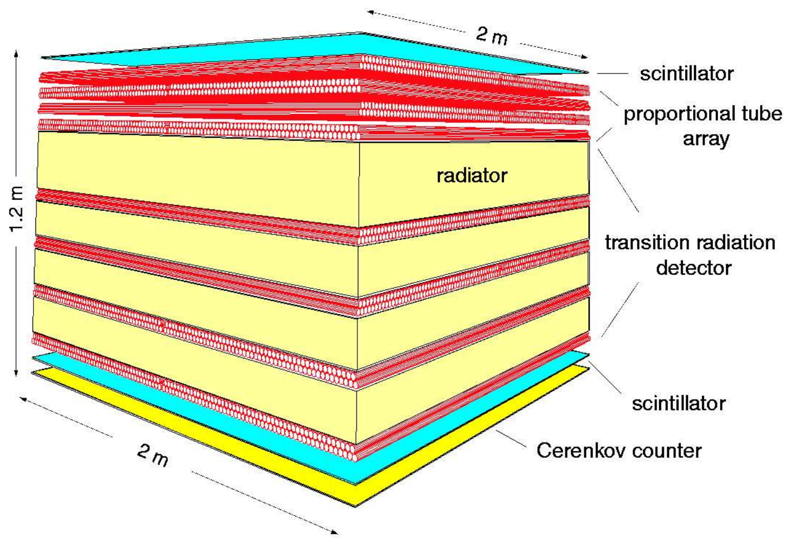

Figure 1. Schematic drawing of TRACER

wire proportional chambers (MWPCs), permits the operation of the detector in a low-pressure environment, thus making the use of a heavy pressure vessel unnecessary.

3. Detector Response

Each of the sub-detectors generates a signal which is essentially proportional to the square of the particle charge and which exhibits a characteristically different response to the energy E or Lorentz factor γ = E/mc^2 of the particle. It is the interplay between the detectors that permits the precise identification of charge and energy of cosmic ray nuclei.

Cherenkov Response and Specific Ionization in Scintillators and Gas Counters

The two scintillation counters each consist of 8 sheets of BICRON 408 with each sheet measuring 100 x 50 cm^2 in area. While the counters are only 0.5 cm thick, the light yield, detected with 24 photomultipliers (PMT) via wavelength shifter bars, is $\sim$ 40 photoelectrons for singly charged particles, sufficient to provide single charge resolution for the heavier nuclei. The light yield increases with Z^2 but deviates from strict proportionality by 15 % for iron.

The Cherenkov counter is composed of four sheets of acrylic material (100 x 100 x 1.27 cm^3) which is doped with blue wavelength shifter. The Cherenkov threshold is $\gamma \approx$ 1.35, and the light output in saturation is about 2 - 3 photoelectrons per Z^2, again measured with 24 PMTs via wavelength shifter bars. Figure 2 displays the "ideal" response for this material (labeled "CER").

As the counter is located at the bottom of the TRACER detector the response function is considerably modified due to δ-rays produced while the particle propagates through the detector material above the counter. The addition of the δ-rays leads to an enhancement of the signal and raises the saturation energy from $\gamma \approx$ 4 to $\gamma \approx$ 10. This effect is understood and has previously been studied quantitatively [3]. The modified response is

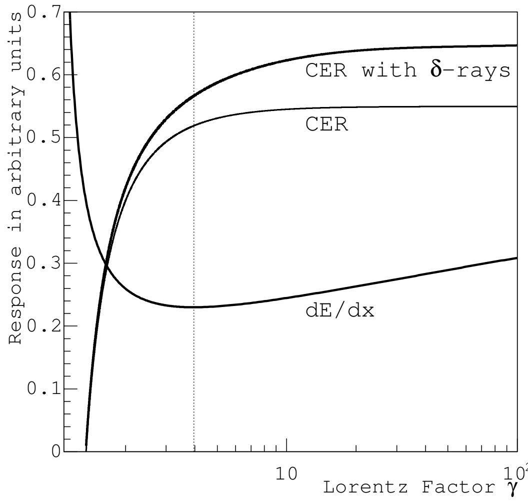

Figure 2. Energy response of the Cherenkov counter with and without taking into account the δ-rays and response function of the specific ionization detector. The dashed line indicates minimum ionization.

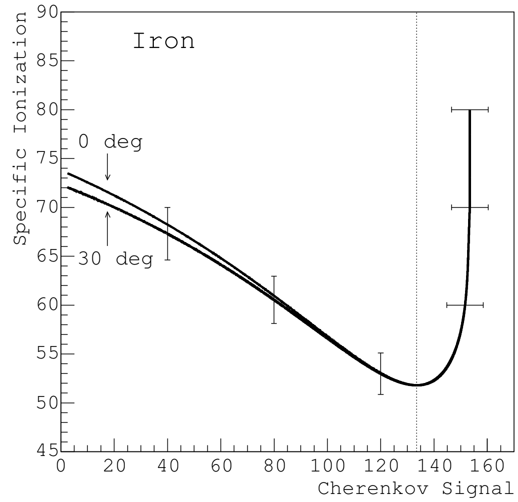

Figure 3. Correlation of specific ionization and Cherenkov signals. The error bars indicate 1 σ fluctuations. The two lines on the low energy end represent 0° and 30° incidence angle (see text). The units are arbitrary.

displayed in figure 2 (labeled "CER with δ-rays").

The prime purpose of TRACER is a measurement of cosmic-ray nuclei at the highest energies. This is accomplished with the dE/dx – TRD system which contains 1600 proportional tubes as active detector elements. Each tube has a wall of 150 μm of aluminized mylar, is 200 cm long and 2 cm in diameter and is filled with a mixture of xenon and methane.

The TRD system is designed for measurements from $\sim$ 400 GeV/amu to energies well exceeding 10,000 GeV/amu. Particles at these energies are extremely rare, and care must be taken to insure that no misidentification of particles with lower energies occurs due to fluctuations in response. To accomplish this the dE/dx system is essential. This system utilizes the relativistic rise in the specific ionization to discriminate highly relativistic particles from those with lower energies. The measurement of the specific ionization also provides an estimate of the particle energy from 10 - 400 GeV/amu.

However, the specific ionization response, well described by the Bethe-Bloch equation, is degenerate in energy below and above minimum ionization (see dE/dx curve in figure 2). The signal of the Cherenkov counter breaks this degeneracy. The correlation of dE/dx and Cherenkov detector is shown in figure 3. The dashed line indicates how a cut on the Cherenkov signal effectively suppresses low energy particles. In practice, this correlation also provides a normalization of the response curves of both the dE/dx detector and the Cherenkov counter [2]. As shown in figure 3 the correlation has a slight dependence on the zenith angle at the lowest energies. This dependence is due to the fact that particles on inclined trajectories traverse more material and hence, lose more energy by ionization on their way from the dE/dx detector to the Cherenkov counter.

Energy Measurement with the TRD

The key to using a TRD is that the energy response can be calibrated with singly charged particles at accelerators over a wide range of Lorentz factors. The radiators used to generate TR in TRACER are made from

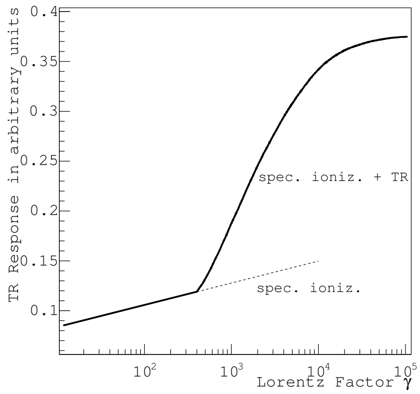

Figure 4. Energy response of the Transition Radiation Detector

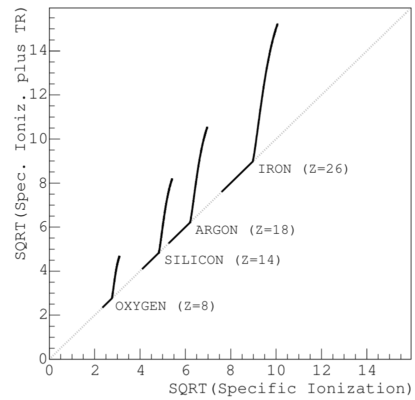

Figure 5. Correlation of responses of Transition Radiation and specific ionization detectors. Four elements are displayed to illustrate the charge dependence of the responses.

plastic fibers and are the same that were used on the Cosmic Ray Nuclei detector (CRN, [4]). The response for this detector is shown in figure 4.
In practice, the combined responses of dE/dx and TRD are used to measure the energy. The correlation of these two responses is displayed in figure 5. Up to 400 GeV/amu both the dE/dx and TRD signals are due to ionization only and are therefore the same. Above this energy TR becomes observable and lifts the correlation above the diagonal. This allows the identification of the very rare highest energy events with no low-energy background.

4. Outlook

The following three contributions to this conference will describe the analysis of the data obtained from the long-duration flight of TRACER in Antarctica [2] and the derivation of the energy spectra of the individual elemental species [5], and will discuss the relevance and astrophysical implications of the results [6].

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