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The TRACER instrument: A balloon-borne cosmic-ray detector

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ABSTRACT

We describe a large-area detector for measurements of the intensity of cosmic-ray nuclei in balloon-borne exposures. In order to observe individual nuclei at very high energies, the instrument employs transition radiation detectors (TRD) whose energy response extends well beyond 10^4 GeV amu^{-1}. The TR measurement is performed with arrays of single-wire proportional tubes interleaved with plastic-fiber radiators. An additional energy determination comes from the specific ionization in gas and its relativistic rise which is also measured with proportional tubes. The tubes also determine the trajectory of each cosmic-ray nucleus with mm-resolution. In total, nearly 1600 tubes are used. The instrument is triggered by large-area plastic scintillators. The scintillators, together with acrylic Cherenkov counters, also determine the nuclear charge Z of each cosmic-ray particle, measure the energy in the GeV amu^{-1} region, and discriminate against low-energy background. We describe the details of this detector system, and discuss its performance in three high-altitude balloon flights, including two long-duration flights in 2003 and 2006 at Antarctic and Arctic latitudes, respectively. Scientific results from these flights are summarized, and possible future developments are reviewed.

1. Introduction

Direct observations of cosmic rays must be performed above the atmosphere, either on spacecraft or high-altitude balloon. The particle intensities decrease rapidly with increasing energy. Hence, large area detectors are required for measurements at high energies. If instruments of several square meters in area are available, and exposed for hundreds of days, the measurements may approach the energy region around 10^{15} eV particle^{-1}. It is often suspected that in this energy region, the cosmic-ray compositions changes as the Galactic accelerator approaches a rigidity-dependent cutoff [1]. Clear evidence from direct observations for such a change does not yet exist. At still higher energies, direct measurements that can identify the primary cosmic-ray particle are not possible with currently available instrumentation, and one must resort to indirect observations of air showers in the earth's atmosphere [2,3].

We will describe here an instrument that has been developed for long-duration balloon flights with the goal of measuring the details of the elemental composition and energy spectra of cosmic-ray nuclei at as high an energy as possible. The mass of a balloon payload is limited to at most a few tons. Within this constraint, measurement techniques that rely on electromagnetic interactions can maximize the detector area more efficiently than techniques utilizing nuclear calorimetry. For the instrument discussed here, transition radiation detectors (TRD) are used, and are augmented with Cherenkov counters and with detectors that measure specific ionization in gas.

Transition radiation detectors (TRD) are sensitive to particles with very high Lorentz factors γ. TRD's are often used in particle physics or cosmic-ray experiments as threshold devices to discriminate between light and heavy particles of known momentum, for instance between electrons, pions, and protons. An accurate determination of the energy of a particle from a measurement of the transition radiation (TR) intensity is much more difficult for singly charged particles because of the large signal fluctuations. The situation becomes qualitatively different if one deals with highly charged particles such as cosmic-ray nuclei: the relative magnitude of fluctuations decreases with Z (where Z is the charge number), and rather precise measurements of the energy (or Lorentz factor) can be made.

Key features of TRD's include: (a) a favorable area-to-weight ratio, (b) the possibility of accelerator calibrations with beams of

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electrons or pions at large Lorentz factors, for which beams of nuclei are not available, (c) the fact that the TR-signal scales strictly with Z^2. Therefore, relative signal fluctuations decrease as $1/Z$, (d) a good match between the Lorentz-factor range of a TRD (10^2–10^5) and the range of energies that can be reached in direct cosmic-ray measurements with reasonable exposure factors, (e) the possibility of multiple redundant measurements in a layered radiator/detector configuration, and (f) good energy resolution, typically of the order of 10% or better for the heavier nuclei at $\gamma \approx 1000$.

The use of a TRD for precise cosmic-ray energy measurements was first demonstrated by the cosmic-ray group at the University of Chicago with a large detector called CRN ("Cosmic-Ray Nuclei instrument"). Like most TR detector systems, CRN employed a sandwich configuration of several radiators and multi-wire proportional chambers (MWPC's), each radiator being followed by an MWPC. The MWPC's had thin, planar windows and operated at atmospheric pressure. Necessarily then, the detectors had to be enclosed in a pressurized container. CRN was flown on the space shuttle in 1985 [4]. However, further development and additional flights of CRN were terminated after the Challenger accident in 1986.

Around the same time as Challenger, long duration balloon flights (LDB) around the northern and southern poles became available. LDB offered the possibility of flights of several weeks duration at moderate cost. Therefore, a new balloon payload, TRACER (Transition Radiation Array for Cosmic Energetic Radiation), utilizing the heritage of CRN, was developed for measurements in an unexplored region of the cosmic-ray spectrum. To minimize the weight it was advantageous to design the instrument such that it could be exposed to ambient pressure, without requiring a pressurized gondola. This led to the replacement the MWPC's of CRN with arrays of single-wire proportional tubes of that could withstand external vacuum.

In this paper, we explain the measurement principles, describe the TRACER detector, and discuss its performance during the three flights thus far. The scientific results are published elsewhere [5–8].

2. Instrument description and performance

2.1. Overall description and balloon flights

TRACER is designed to measure the energy spectra of the heavier cosmic-ray nuclei from boron (Z=5) to iron (Z=26). In order to reach energies in the 10^{14}–10^{15} eV particle^{-1} region in repeated long-duration balloon flights, the detector has a geometric factor of $\sim 5\ \mathrm{m}^2$ sr and is currently the largest balloon-borne cosmic-ray detector in existence. The instrument is shown schematically in Fig. 1.

TRACER must perform two measurements for each incident cosmic-ray nucleus: (1) identify its nuclear charge Z. Isotopic resolution is not attempted, and, in fact, is beyond current measurement techniques at these energies. (2) measure its energy E or Lorentz factor γ.

Cosmic-ray nuclei at these energies are fully ionized. Therefore, their nuclear charge is determined with two identical pairs of scintillation and acrylic Cherenkov counters placed at the top and bottom of the instrument. The scintillation counters also provide the instrument with a coincidence trigger. The charge measurement utilizes the fact that both the ionization energy loss generating the scintillator signal, and the Cherenkov light yield, scale with Z^2. However, the energy dependence in both counters is characteristically different. Consistency in the charges measured on top and bottom, respectively, ensures that nuclei have not undergone a charge-changing nuclear interaction within the detector.

Layers of gas-filled single-wire proportional tubes (a total of 1584, each 2 m in length) between the top and bottom counters measure the specific ionization $\langle dE/dx \rangle$, or form a transition radiation detector (TRD) which measure $\langle dE/dx + \mathrm{TR} \rangle$. Both, the d$E$/d$x$ and TR signals scale with Z^2.

TRACER determines the energy of individual cosmic-ray nuclei in three regions: (a) at low energies, up to a few GeV amu^{-1}, from the signals of the Cherenkov counters, (b) from about 10–400 GeV amu^{-1} from the relativistic increase of the ionization signal measured in the proportional tubes, and (c) above 400 GeV amu^{-1}, from the signals of the TRD (see Fig. 2). The TRD is expected to saturate at energies around 30,000 GeV amu^{-1}. Because of the steeply falling energy spectrum, TRACER cannot cover energies beyond this region.

As mentioned, statistical fluctuations in the dE/dx and TR signals preclude energy measurements for low-Z particles, such as protons and helium nuclei with this instrument.

The instrument includes various analog and digital electronic circuits to read out the detector subsystems, format and store the data onboard, receive commands and transmit data to the ground. To save weight, the entire detector, apart from a small number of pressure sensitive electronic devices, operates at ambient pressure during the balloon flights. This creates a number of technical challenges, including the danger of corona discharge at the detector elements under high voltage, and local overheating of the electronics. The proportional tubes have an on-board gas supply and regulation system that allows for regulation of the gas pressure in flight. Electric power during the LDB flights comes from onboard photovoltaic solar arrays. Passive thermal protection for TRACER is provided through the use of foam insulation and Mylar sun shields. Fig. 3 shows the TRACER instrument ready for launch in Antarctica in 2003.

TRACER has had three successful flights on high altitude balloon thus far. For each flight a 39 million cubic-foot balloon was used. Typical float altitudes were 36–40 km, corresponding to a residual atmosphere of 3.5–6 g cm^{-2}. The instrument and data

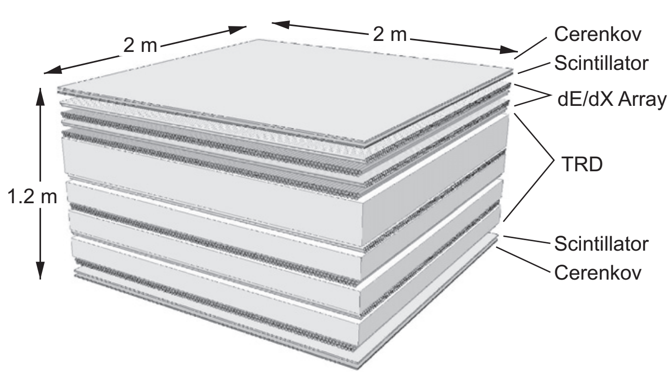

Fig. 1. Schematic diagram of the TRACER instrument.

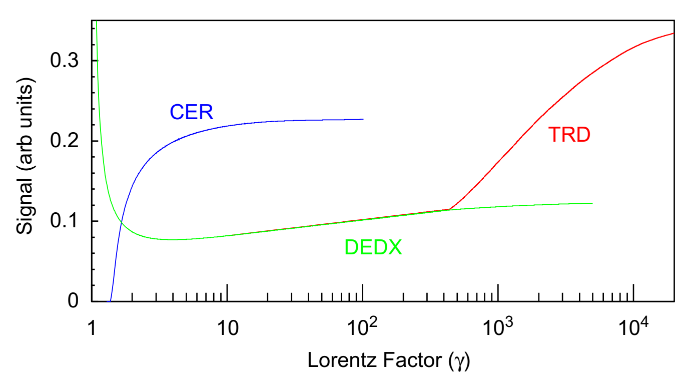

Fig. 2. Energy response of TRACER [6]. Three measurements are combined to cover more than four decades in energy. All signals scale with Z^2.