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A new detector for the measurement of the energy spectrum of cosmic ray nuclei in the TeV region*

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A new instrument for direct measurements of the individual energy spectra of heavy cosmic-ray nuclei in the energy range from 10^{11} to several 10^{14} eV shall be described. The instrument performance is discussed, using first results from a 28-hour balloon flight and from an accelerator calibration.

1. INTRODUCTION

The individual energy spectra of heavy cosmic rays are poorly known above a TeV/nucleon. The goal of TRACER (Transition Radiation Array for Cosmic Energetic Rays) is to measure these spectra in the energy range from 10^{11} to several 10^{14} eV.

It is planned to achieve this goal in three stages: a standard balloon flight and two long-duration balloon flights.

The first balloon flight was conducted in September 1999 from Ft. Sumner/New Mexico. The payload has been 28 hours at operating altitude with less the 6.5 g/cm^2 residual atmosphere above the detector. All detector components were operating successfully. First results of this flight will be discussed in the following.

To increase the statistical quality of the data, a circum terrestrial flight of 14 days is planned for June 2001 from Fairbanks/Alaska. The currently used electronics, which was taken over from previous experiments, has limited dynamic range, and therefore restricts the charge range to nuclei from oxygen to iron. A new read-out system, allowing to cover the charge range from lithium to nickel, will be developed for another flight, planned for 2003.

2. DETECTOR SET-UP

TRACER measures the nuclear charge, the energy, and the trajectory through the instrument for each single cosmic ray nucleus. The particle energy is determined from measurements of the ionization loss in gases, and with a transition radiation detector (TRD). This approach permits the construction of large-area detectors without requiring an exorbitant detector mass. A schematic view of the detector system with a geometric factor of about 5 m^2 sr is shown in figure 1.

TRACER consists of eight double layers of 98 proportional tubes each which are oriented alternately in two orthogonal directions in order to determine the particle trajectory. The proportional tubes are 2 m long and 2 cm in diameter, consisting of aluminized Mylar with a wall thickness of 125 μm, and are filled with a xenon–methane mixture. The ionization losses of the particles are measured with the four upper double layers forming a proportional tube array. Four radiators of plastic fiber material, previously used in the CRN experiment [1], each followed by a double layer of proportional tubes, form a TRD to measure the particle energy.

Two scintillators ($200 \times 200 \times 0.5$ cm^3), placed on top and bottom of the detector stack, act as instrument trigger. In addition, the charge is determined through measurement of the specific ionization. A Čerenkov counter ($200 \times 200 \times 1$ cm^3) of acrylic plastic at the bottom of the detector is used to reject non-relativistic particles. The scintillation and Čerenkov counters are read out with photomultiplier tubes via wavelength shifter bars.

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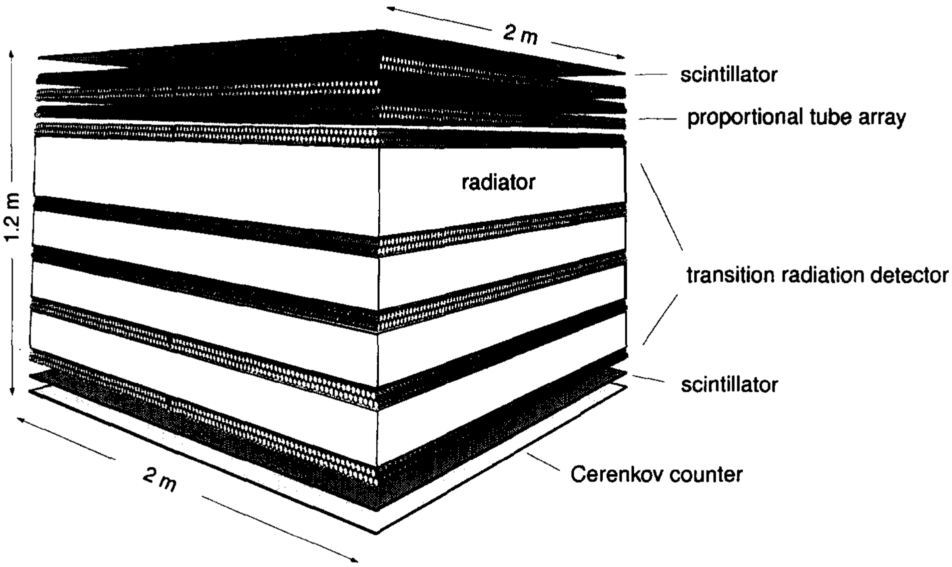

Figure 1. Schematic view of the TRACER detector system.

3. ACCELERATOR CALIBRATION

One of the main advantages of this detector system is the possibility of an absolute calibration at a test beam of singly charged particles. The response of the proportional tube array as well as the TRD system depends on the Lorentz factor $\gamma = E/mc^2$ of the particle. Scaling with Z^2 then permits one to predict the response to heavy nuclei.

The calibration was conducted from November 1999 to January 2000 in the fixed target area at Fermilab, using a secondary beam with energies from 3 up to 227 GeV.

As an example, the detector response for 35 GeV electrons is shown in figure 2. The energy deposit in the proportional tube array exhibits the typical Landau distribution. The signals in the TRD can be described as the superposition of a Landau function to describe the ionization losses and a second function to describe the energy deposit due to transition radiation photons. The parametrisation

$$f(\lambda) = \frac{C}{\sqrt{2\pi}} e^{-\frac{1}{2}(s\lambda + e^{-\lambda})} \text{ with } \lambda = \frac{\Delta E - E^*}{\xi}$$

with the parameters C, E^*, ξ, and s can be used to describe both components of the signal, ionization and transition radiation. The function gives

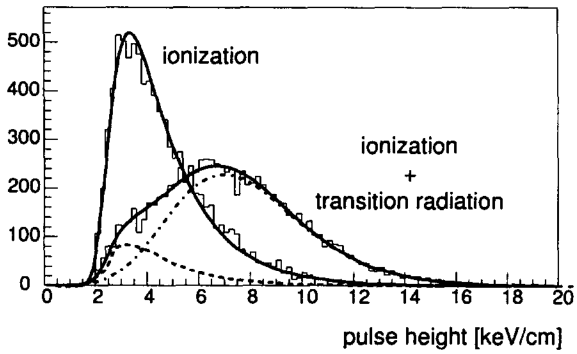

Figure 2. Measured energy deposit of 35 GeV electrons in the TRACER proportional tubes filled with a (50%,50%) xenon–methane–mixture.

the probability for an energy deposit ΔE, and the parameters s and E^* depend on the Lorentz factor. $f(\lambda)$ represents a Landau distribution for $s \equiv 1$ [2].

4. INSTRUMENT PERFORMANCE

The analysis of the first balloon flight is presently (June 2000) in progress; first results are presented in the following.

Detailed Monte–Carlo calculations for the detector response of the complete TRACER system have been performed, using the detector simulation tool GEANT4 [3]. δ–ray production is an important contributor to the fluctuations of the energy deposit for heavy nuclei. As the present version of GEANT does not include δ–ray production for heavy ions, these, with charge Z, were simulated by superimposing $N = Z^2/\zeta^2$ lighter particles with charge ζ.

4.1. Signal fluctuations

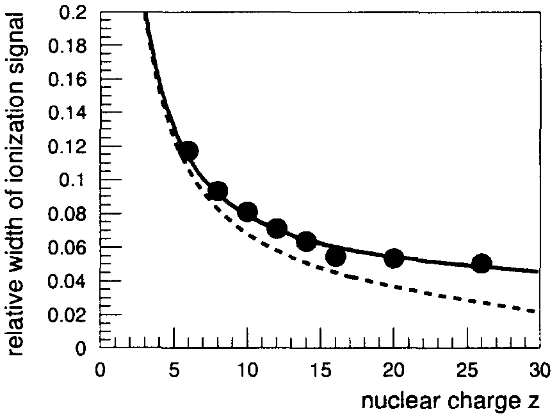

Figure 3. Measured relative width of ionization signal as function of the nuclear charge.

Once the track of a particle through the detector is known, the specific ionization of each particle can be measured. The relative width of the ionization signal in the proportional tubes is shown in figure 3 as function of the nuclear charge Z. The relative width of the signal decreases with Z and can be described by the function $\Gamma_\sigma^2(Z) = a^2/Z^2 + b^2$, with the parameters $a = 0.69$ and $b = 0.04$. The dashed line is the result of simulation calculations, including the intrinsic fluctuations of the energy deposit and the uncertainties introduced by the track reconstruction. Additional signal fluctuations of 4% due to the finite resolution of the proportional tubes and due to amplifier gain variations lead to the solid curve.

4.2. Track reconstruction

The perpendicular arrangement of the proportional tubes allows to reconstruct the trajectories of particles traversing the detector. Since the energy deposit in a proportional tube is proportional to the pathlength of the particle in this tube, the position of the trajectory relative to a tube can be obtained with a precision much better than a tube diameter. The spatial resolution of the track reconstruction is shown in figure 4 as function of the nuclear charge. The signal fluctuations of singly charged particles are relatively large (see figure 2). A maximum liklihood method taking the asymmetric Landau fluctuations into account is used to determine the particle trajectory in this case. It leads to a spacial resolution of 2.5 mm. The relative signal fluctuations decrease with the particle charge as demonstrated in figure 3. For heavy nuclei, the deposited energy exhibits a symmetric, Gaussian distribution, allowing to reconstruct the tracks with much better precision. Resolutions from 1 mm to 0.25 mm are achieved for oxygen and iron, respectively.

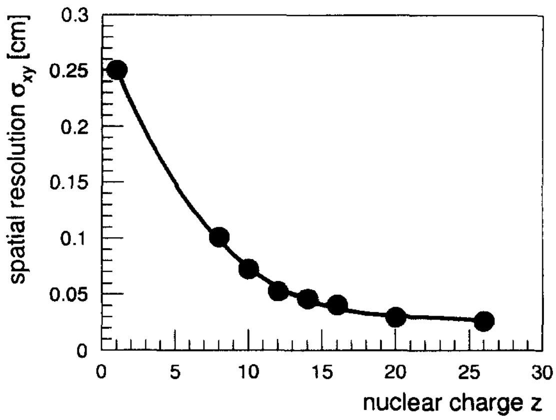

Figure 4. Spatial resolution of the track reconstruction as function of the nuclear charge.

4.3. Energy Resolution

The energy resolution of the detector system depends on the signal fluctuations as shown in figure 3, the relativistic rise of the ionization loss, and the magnitude of the transition radiation signal as a function of the Lorentz factor. Results from the balloon flight and the accelerator calibration lead to an energy resolution as shown in figure 5 as a function of the Lorentz factor γ for

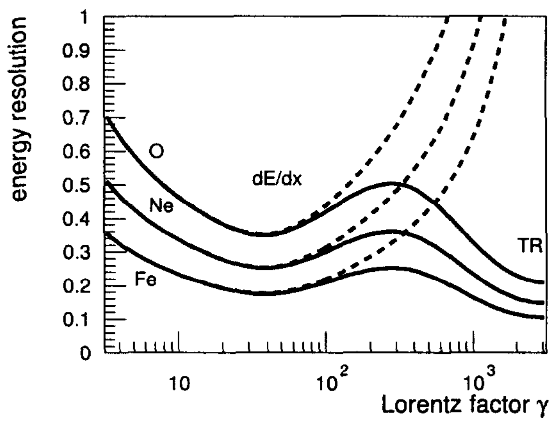

Figure 5. Energy resolution as function of the Lorentz factor γ of the cosmic–ray particles.

different species. The two detection techniques used in TRACER have their best energy resolution in two different energy regimes. The ionization measurements achieve best resolution around $\gamma = 32$ of about 18% for iron and 35% for oxygen. The transition radiation measurements allow more precise measurements beyond $\gamma = 1000$ with best resolutions of 11% for iron and 21% for oxygen.

4.4. Measured charge distribution

The two scintillators and the Čerenkov counter provide a signal essentially proportional to Z^2 and independent of the particle energy. Knowledge of the spatial response function of each counter as well as the non-linear response of the scintillators for higher charges allows to calculate the charge of the measured particles. The measured charge distribution for relativistic nuclei is shown in figure 6. The main cosmic-ray elements from boron to iron can be identified. The charge resolution is about 0.22 charge units for oxygen. It is remarkable that this resolution can be achieved with a 4 m^2 scintillator, just 5 mm thick, and read–out by just 12 photo multiplier tubes via wavelength shifter bars.

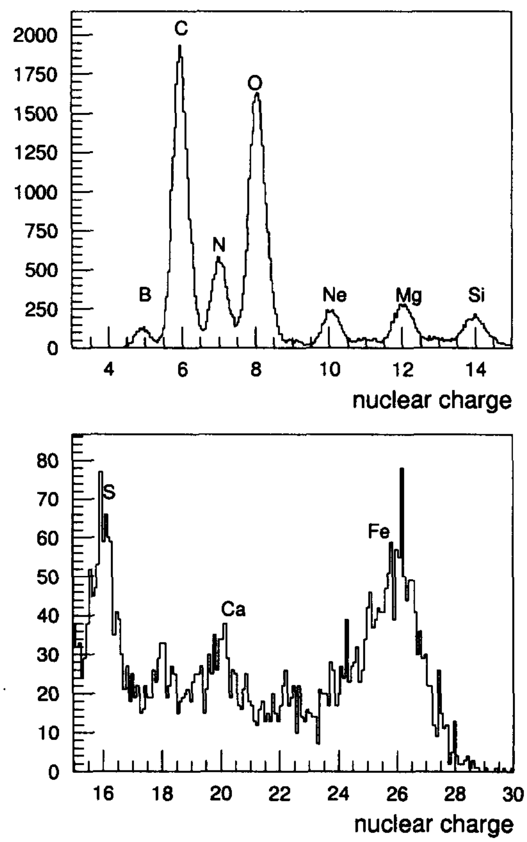

Figure 6. Measured charge distribution for relativistic cosmic–ray nuclei.

5. CONCLUSION

The successful balloon flight and the accelerator calibration of the detector show that the new instrument to measure the energy spectra of heavy cosmic–ray nuclei is working as expected. We expect to soon be able to present physics results from this investigations.

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