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A new measurement of the energy spectra of cosmic-ray nuclei

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Abstract. A new large-area detector system was constructed at the University of Chicago for direct measurements of heavy cosmic ray nuclei (oxygen to iron) up to about 10 TeV/nucleon. TRACER ("Transition Radiation Array for Cosmic Energetic Radiation") uses plastic scintillators to measure charge and a proportional tube array to measure energy via specific ionization and transition radiation. While TRACER is designed for circumglobal long-duration balloon flights, an initial 28-hour flight was conducted in Autumn 1999 from Ft. Sumner, New Mexico. We will discuss the performance of the detector and present first data from the balloon flight.

1 Introduction

While the overall energy spectrum of cosmic rays extends beyond 10^{20} eV/particle, present data on composition and spectra of the individual components are scarce at energies above several 10^{13} eV/particle. Consequently, current ideas about particle acceleration and propagation lack some important constraints over much of the high–energy region, including the *knee* around $3 \cdot 10^{15}$ eV/particle. New observations with large–area detectors and long exposure times are required to improve this situation. The TRACER program ("Transition Radiation Array for Cosmic Energetic Radiation") attempts to address this need. The TRACER instrument has been flown in a conventional balloon flight in autumn 1999, and is presently prepared for a long–duration flight in 2002. TRACER also serves as a prototype for a detector that could eventually be used as an attached payload on the Space Station. Here we shall report on the performance of the instrument and on the data obtained in the first balloon flight in 1999.

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2 Description of the Instrument

In order to obtain a detector with a favorable weight to area ratio, we employ gaseous detectors that determine the particle energy via the logarithmic dependence of the specific ionization on the Lorentz factor $\gamma = E/mc^2$ of the particle, or via the detection of transition radiation (TR) at the highest energies. In this fashion, the Lorentz factor range from less than 10 to at least 10^4 can be covered for nuclei with charge $Z > 3$. Protons and helium are not included since the statistical fluctuations become too large as to permit a reliable measurement of γ for these low–Z elements with this technique. The TR measurement follows a concept first developed for the CRN instrument flown on the Space Shuttle in 1985 (L'Heureux et al. 1990), and the accelerator calibrations originally performed for CRN are also applicable for TRACER. However, the TR detector of CRN consisted of thin–window multiwire proportional chambers at atmospheric pressure, and the instrument had to be enclosed in a pressurized shell. For TRACER, the wire chambers are replaced by layers of single wire–proportional tubes which easily withstand external vacuum. Hence, a pressurized container is not needed.

TRACER is shown schematically in figure 1. The main elements are:

1. Two square scintillators, each 2 m $\times$ 2 m in area, on top and bottom of the instrument. These serve as coincidence triggers and determine the nuclear charge Z of cosmic–ray particles. Each scintillator sheet is just 5 mm thick and is viewed by 12 photomultiplier tubes (PMT) via wavelengthshifter bars.

2. An acrylic Cherenkov counter, 2 m $\times$ 2 m in area, located below the bottom scintillator, to reject sub–relativistic nuclei.

3. An array of eight layers of proportional tubes, each tube 2 cm in diameter and 200 cm long, to measure the specific ionization of traversing cosmic rays.

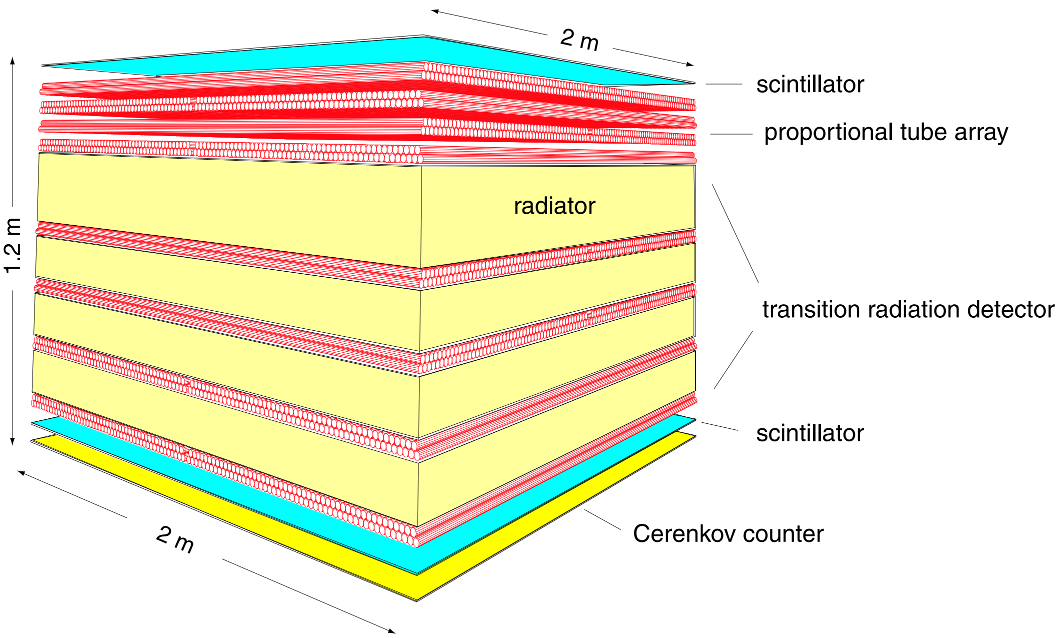

Fig. 1. Schematic view of the TRACER detector system.

4. A transition radiation detector (TRD) consisting of a stack of four radiator detector combinations: The radiators are battings of polyolefin fibers, identical to those of CRN (L'Heureux et al. 1990), and each detector comprises a double layer of proportional tubes. All tubes are filled with a Xe/CH_4 mixture.

The signal read–out is accomplished by analyzing each of the 64 PMT signals with 12 bit resolution, and by analyzing each of the 1600 proportional tubes with 8 bit resolution, using VLSI electronics. Limitations in the dynamic range of the electronics available to us when TRACER was constructed, restrict the range to $7 < Z < 28$ for the first TRACER flight.

3 Balloon Flight

The first balloon flight of TRACER was conducted from Ft. Sumner, N.M., on September 20/21 1999. The instrument floated at an altitude corresponding to 4 to 6 g/cm^2 of residual atmosphere for a duration of 28 hours, and was safely recovered by parachute. The average geomagnetic cutoff rigidity was 4.5 GV. During the flight, the instrument detected a total of 1.3 million events, corresponding to about 500 MByte of raw data which were recorded on board and simultaneously received by telemetry on ground.

4 Data Analysis and Results

The data analysis proceeds in the following steps:

4.1 Charge measurement and trajectory information

The elemental charge Z is determined primarily from the signals of the two plastic scintillators. The specific ionization is proportional to Z^2, but for iron (Z=26), the density effect reduces the measured signal by 29% from proportionality to Z^2. However, light collection from the scintillator exhibits spatial non–uniformities of about a factor of 2. Hence response maps for the scintillators, generated with cosmic–ray muons on ground, and confirmed by the flight data, are used to normalize the scintillator signals. Therefore, the trajectory of each particle must be determined first. This is obtained in two steps. First, the positions of all tubes with signals above threshold provide 16 measurements, each with 2 cm resolution. A least–square fit to the center positions of these tubes determines the trajectory with a lateral accuracy of about 5 mm. Second, we use the fact that the magnitude of the signal in each tube is proportional to the path length of the particle through the tube, within statistical fluctuations. Taking this into account in the fitting procedure, we improve the lateral accuracy to 1 mm for oxygen and 0.25 mm for iron (Hörandel et al. 2001).

Figure 2 shows a charge spectrum obtained from the corrected signals of the scintillators and of the Cherenkov counter, with the additional requirement that the signals in the top and in the bottom scintillators are consistent with each other within resolution limits. This requirement rejects nuclei that may have undergone a nuclear interaction in the instrument. The charge resolution is about 0.22 charge units for oxygen. Note that the charge resolution around iron will further improve when the data are corrected for some distortions due to occasional PMT–saturation.

4.2 Determination of the Energy Spectrum

After assignment of nuclear charge Z, we investigate the signals from the proportional tubes. The upper 8 layers measure the specific ionization, which increases logarithmically with γ. The lower eight layers again measure the ionization sig-

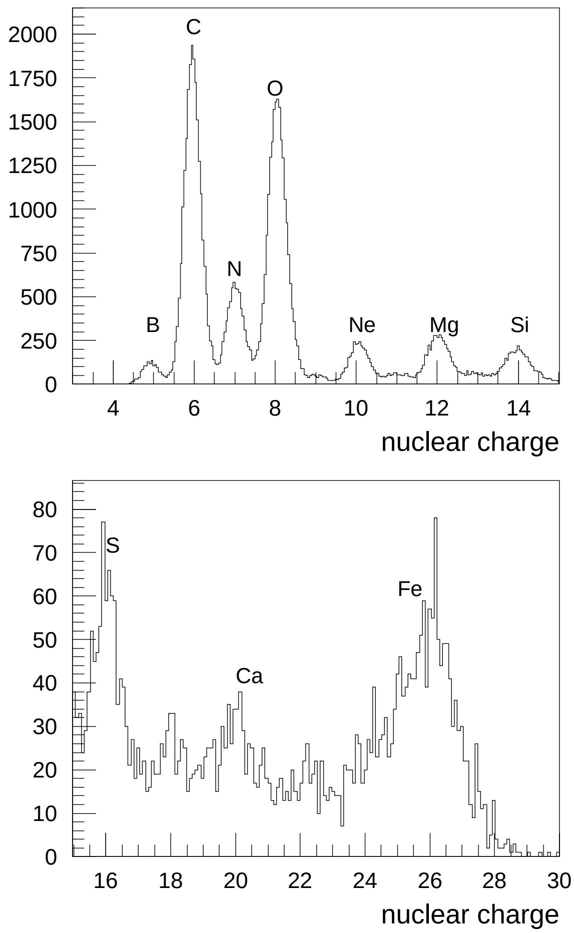

Fig. 2. Measured charge distribution for relativistic cosmic–ray nuclei.

nal, but for large energies ($\gamma > 500$), transition radiation signals are superimposed. As the signals depend on the pathlength through the tube, knowledge of the trajectory again is important for the analysis. For each set of double layers, we determine the total signal, normalized to the total pathlength and use this number for further analysis.

For the analysis, we make extensive use of the GEANT 4 code (CERN 2001), which simulates both ionization loss and transition radiation. We first verify that the code properly reproduces the data obtained in accelerator calibrations (L'Heureux et al. 1990) (Swordy et al. 1990). We than generate simulated data: We subject a realistic model of the TRACER instrument, which includes the actual detector geometry, mass distribution, etc. to an isotropic flux of simulated cosmic rays with an assumed primary energy spectrum with a spectral index of -2.7 and a geomagnetic cut–off of 4.5 GV. The simulation takes all interactions, including nuclear fragmentation, δ–ray production, TR generation, etc., into account, including realistic statistical fluctuations. Each particle and each X–ray photon is followed, and simulated proportional tube signals are obtained.

In figure 3 we illustrate the procedure by showing a scatter plot for simulated signals for oxygen nuclei ($Z = 8$) versus

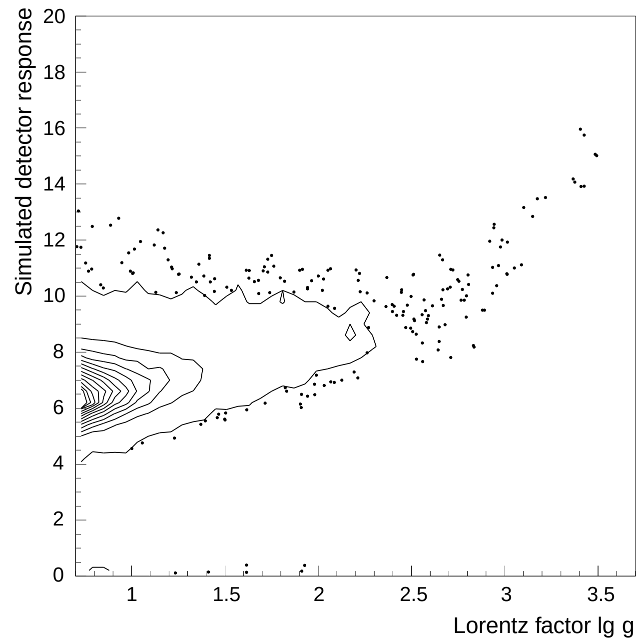

Fig. 3. The simulated detector response vs. Lorentz factor for oxygen nuclei as detected by the TRD.

their Lorentz factor γ. A primary spectrum $\propto \gamma^{-2.7}$ is assumed. The simulated data in the figure are the signals just from the TRD part of the detector system. The trend of the data is characterized by a slow increase in spezific ionization up to a Lorentz factor $\gamma \approx 500$, followed by a stronger

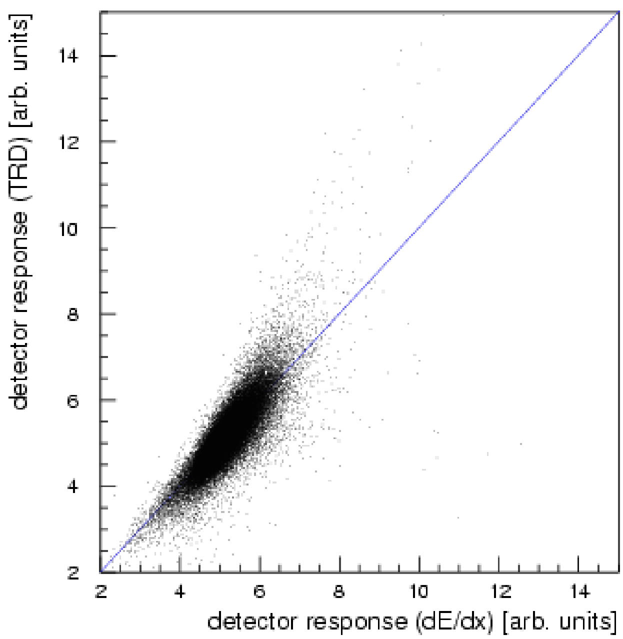

Fig. 4. Measured detector response of the TRD versus the proportional tube array. Raw data for oxygen nuclei, as taken during the balloon flight are shown.

increase due to TR. The figure also illustrates the spread of the data due to fluctuations in detector response. The possibility that such fluctuations will cause a low–energy particle to mimic a high–γ event, can be strongly reduced if one requires consistency between the signals of the TRD and of the proportional tube array that estimates the particle energy from the relativistic rise in ionization loss only.

The correlation between TRD signals and ionization loss measurements are shown in figure 4, using oxygen data, taken during the balloon flight. While for low Lorentz factors the signals of both detectors are proportional to each other, for higher energies we see a systematic enhancement in the TRD signals over those of the ionization detectors.

A formal analysis to extract the shape of the energy spectra for the different nuclear cosmic ray species from the measured data is presently in progress. We will present the resulting spectra at the time of the conference.

5 Conclusion

A successful standard balloon flight with the TRACER system shows that the instrument is working as expected. A analysis procedure to reconstruct the energy spectra of cosmic–ray nuclei has been developed using a detailed detector simulation. Energy spectra for individual elements will be presented at the conference.

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