A New Detector for Measurements of the Composition of Heavy Cosmic Ray Nuclei beyond TeV-Energies

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Abstract

A new instrument for direct measurements of heavy cosmic ray nuclei (oxygen to iron) in the energy range from about 10^{13} to several 10^{14} eV is described. The detector consists of a counter telescope with a proportional tube array and a transition radiation detector. Single wire proportional tubes are used which allow operation in the low pressure environment of stratospheric balloons without requiring a pressurized gondola. The first two balloon flights for the instrument are scheduled during fall 1999 and summer 2000.

1 Introduction:

Measurements of the energy spectra of cosmic ray nuclei with individual–element resolution and fair statistics presently extend to energies somewhat above a TeV/nucleon (Shibata 1996). Extrapolated towards the cosmic ray source, the measurements indicate source spectra for all elements of the form $E^{-2.15}$, at relative abundances at the source which are anticorrelated with the first ionization potential (FIP). For this extrapolation, the galactic propagation pathlength is taken to decline with energy as $E^{-0.6}$ (Swordy et al. 1990a). While the origin of the FIP–effect is not well understood, the form of the source spectrum coincides with expectations for the shock acceleration process in supernova–driven shock fronts. This mechanism is likely to become inefficient at energies around ≈ 50 TeV/nucleon (Lagage et al. 1983), and changes in the spectral shape and elemental composition are then expected to occur. This energy region is not only unexplored by direct measurements, but also the propagation pathlength, essential for deducing the source spectra from those measured near Earth, is not known at energies above about 0.1 TeV/nucleon.

The experimental obstacles towards measurements at high energies are the low particle flux, necessitating exposure factors in excess of 100 m^2 sr days even for the more abundant primary nuclei (heavier then H and He), and the difficulty of precise energy measurements that can be calibrated at accelerators. In this paper we describe an instrument that should provide measurements up to about 10 TeV/n. The detector system TRACER ("Transition Radiation Array for Cosmic Energetic Radiation") is beeing prepared for its first balloon flight and uses the transition radiation (TR) technique for energy measurements which was first applied by our group in a measurement on the Space Shuttle in 1985 (Müller et al. 1991), and it will achieve substantial exposure times in long–duration balloon flights. For reasons of limited dynamic range in the VLSI front end electronics presently available to us, the first balloon flight will concentrate on measurements of the heavy nuclei, oxygen $(Z = 8)$ to iron $(Z = 26)$.

2 Detector Concept:

In order to determine the charge and energy of cosmic ray nuclei, TRACER uses a combination of plastic scintillators and Cerenkov counters, and arrays of single wire proportional tubes which are combined with layers of plastic fiber radiators that generate transition radiation. Figure 1 shows the arrangement. The dimensions of the detector layers are about 2×2m^2, and the height of the system is about 1.2 m, leading to a geometric factor of about 5 m^2 sr.

The arrangement is as follows:

- Two scintillators are placed on top and bottom of the detector stack, respectively. They determine the charge Z of relativistic particles via Z^2 dependence of the specific ionization and provide an overall instrument trigger. In addition, consistency in the signals of the two scintillators will be required to identify particles that did not interact in the material of the detector stack.

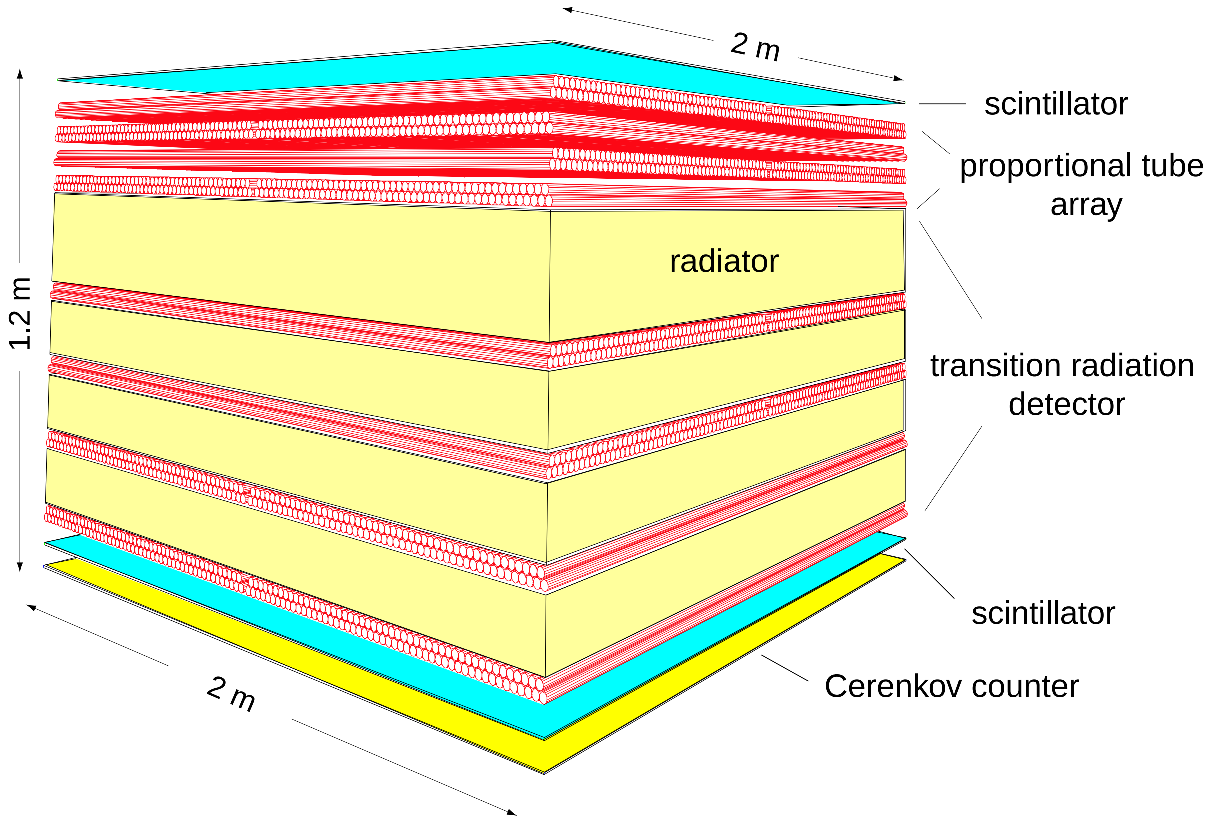

Figure 1: Schematic view of the TRACER instrument.

- A Cherenkov counter made of acrylic plastic at the bottom of the detector is used to reject non-relativistic particles.
- An array of four double layers of proportional tubes (PTA) measures the specific ionization of particles and permits, via the relativistic rise, a crude energy measurement.
- Four radiators of plastic fiber material, each followed by a double layer of proportional tubes, form a transition radiation detector (TRD) to measure the particle energy over the range $500 \leq \gamma = E/mc^2 \leq 10\,000$.

The proportional tubes in all layers of the PTA and the TRD are oriented alternately in two orthogonal directions in order to determine the particle trajectory and thus to permit corrections in the data due to pathlength variations.

This arrangement forms a relatively light weight system at large area. As the proportional tubes, made of aluminized Mylar, can easily withstand zero outside pressure, a pressurized balloon gondola is not required. However, the detector system, with 1584 proportional tubes being individually analysed, requires a large number of data channels. Thus, VLSI electronics is used for data acquisition (the AMPLEX chip).

The signals for an accepted cosmic ray particle must satisfy the following requirements:

- Consistent measurement of charge Z with both scintillators.
- Saturated Cherenkov signal, consistent with Z.
- Unique trajectory through the detector stack.

- Consistent signals in the PTA array above the minimum–ionization level.
- Consistent signals in the TRD. An event will only be accepted as ”highly energetic” $(\gamma > 500)$ if the TRD signals are above threshold, and if the PTA signal is at least 1.5 times that of a minimum ionizing particle.

3 Technical Details and Expected Performance:

The scintillators (Bicron BC 408, 0.5 cm thick) must achieve good charge resolution. Viewed by twelve 19 mm photomultipliers (Philips XP 1910) via wavelengthshifter bars, they detect about 60 photoelectrons for singly charged particles, and the expected charge resolution for iron is then about 0.1 charge units.

The TRD and PTA together consist of 1584 proportional tubes. The tubes have a diameter of 2 cm and are 2 m long. They are produced from three layers, each 25 μm thick, of spiralwound Mylar, the innermost of which is aluminized. At the center of each tube is a stainless steel anode wire of 50 μm thickness. During the flight, the tubes will be filled with a mixture of 50% xenon and 50% methane at 300 torr. The primary ionization produced by heavy nuclei is large so that the tubes can be operated in the ionization mode, with little or no proportional amplification. This reduces fluctuations in the signals. The proportional tube system permits the determination of the particle trajectories with an accuracy of about 1 mm. For the radiators, we use blankets of polyolefin plastic fibers in an arrangement that is identical to the radiator configuration of our previous CRN detector on the Space Shuttle (L'Heureux et al. 1990). The uppermost radiator is 20 cm thick, and the following four radiators are each 12 cm thick. Thus, TRACER performs four independent measurements of the TR signal.

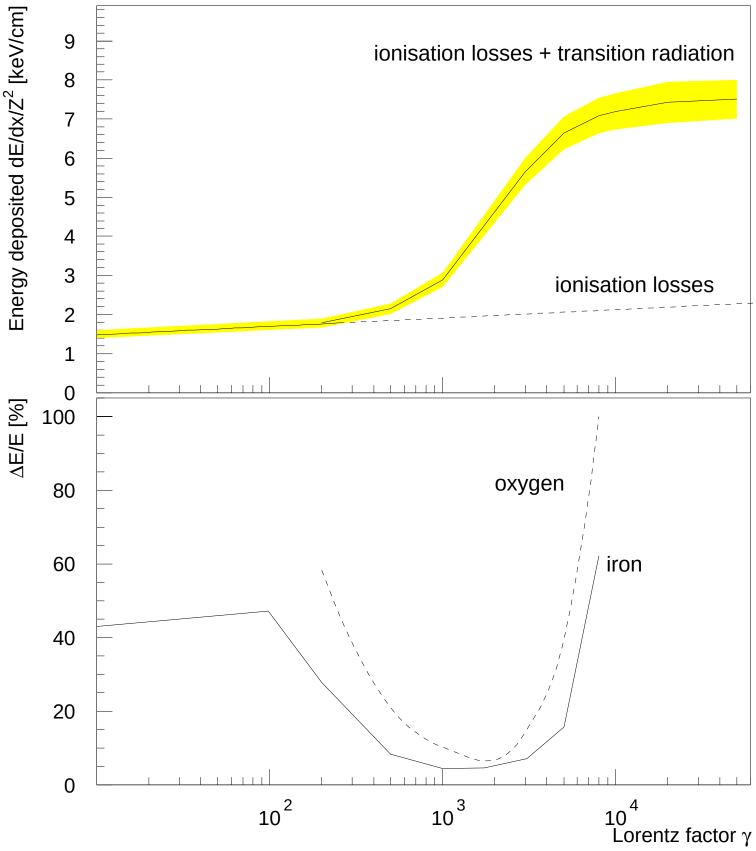

Figure 2: Typical response of a tracer–type TRD to oxygen (upper graph). The dashed line represents the ionization signal without transition radiation that would be measured in the PTA. The expected energy resolution for oxygen and iron nuclei is shown in the lower graph.

The abibility of the PTA and TRD to determine the particle energy depends on the response of the detector and on the fluctuations of this response. Figure 2 shows the simulated response, which also is verified by accelerator calibrations (Swordy et al. 1990b), of the TRD. The upper graph shows the energy deposited in the TRD by charged particles normalized with $1/Z^2$. The energy deposition in the TRD consists of a superposition of ionization energy loss and transition radiation x–rays. The ionization signal alone is independently determined in the PTA tubes. The fluctuations in the signal are determined in the simulation and verified by previous data from the CRN detector. Based on these fluctuations, TRACER can measure the particle energy over the range of 0.1 to 10 TeV/nucleon. The upper end of this energy range is limited by saturation effects in the TRD configuration chosen, but also coincides with the range that can be covered in balloon flights with reasonable statistics. Different radiator configurations can extend the saturation energy by nearly a factor of 10. Figure 2 also shows that at lower energies, from a few GeV/n to 0.5 TeV/n, an energy measurement can be made with about $\Delta E/E \approx 40\%$ resolution for iron, utilizing the logarithmic rise in specific ionization.

4 Calibration and Balloon Flights:

One of the main advantages of this detector system is the possibility of absolute calibration at an accelerator beam. As the response of both the PTA and the TRD depends on the Lorentz factor $\gamma = E/mc^2$, beams of electrons, pions, or protons are available over the entire Lorentz factor range. Simple scaling with Z^2 then permits one to predict the response for heavy nuclei (Swordy et al. 1990b).

The first two balloon flights of the TRACER system are scheduled as a ≈ 40 hour standard flight from New–Mexico during fall 1999, and as a 12 day long duration balloon flight around the north pole from Alaska in 2000, respectively.

The statistical quality of data expected from a 12 day flight corresponding to 60 m^2 sr days is illustrated in Figure 3. The cosmic ray energy spectrum is shown, as usual multiplied by $E^{2.75}$. The expected TRD results cover an energy range from about 10^{13} to nearly 10^{15} eV. The measurements will have a significant overlap with present air shower experiments allowing an improvement of the understanding of the interactions within the atmosphere. For comparison, Figure 3 includes results from CRN on Spacelab 2 (Müller et al. 1991). The TRACER results will allow a differentiation between two possible cosmic ray models, the ”residual pathlength model” where the propagation pathlength reaches a finite value of 0.013 g/cm^2. and the ”leaky box model” which assumes a continuous decrease of the pathlength $\propto E^{-0.6}$.

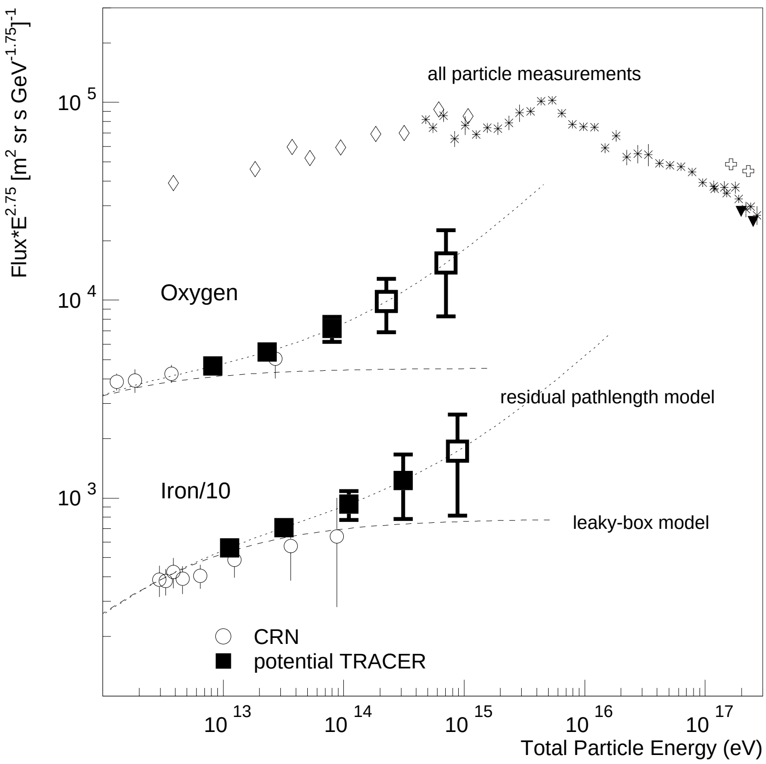

Figure 3: Simulated data for oxygen and iron, indicating the statistical quality of data from TRACER for a 12 day flight.

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