29th International Cosmic Ray Conference Pune (2005) **00**, 101–104

Energy Spectra of Heavy Cosmic Ray Nuclei from 0.5 GeV/amu to 10,000 GeV/amu

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

(a) Enrico Fermi Institute, University of Chicago, 5640 South Ellis Avenue, Chicago, IL 60637
(b) University of Karlsruhe, Germany
(c) Hirosaki University, Japan
Presenter: P.J. Boyle (jojo@donegal.uchicago.edu), usa-boyle-P-abs1-og11-oral

We present new results on the energy spectra of cosmic ray nuclei which are derived from the long-duration balloon flight of the TRACER detector in Antarctica in December, 2003. The measurements are corrected for detection efficiencies, interaction losses in the atmosphere and in the instrument, and for overlap effects due to limited energy resolution. Hence, we report the absolute intensities at the top of the atmosphere for the cosmic ray nuclei over the charge range from oxygen (Z = 8) to iron (Z = 26). The range of the individual energy spectra extends from about 0.5 GeV/amu to several 1000 GeV/amu for the more abundant species (O, Ne, Mg, Si, and Fe), and to about 1000 GeV/amu for the rarer species S, Ar, and Ca.

1. Introduction

The TRACER detector has observed heavy cosmic-ray nuclei ($8 \leq Z \leq 26$) in a 10-day balloon exposure in 2003. For each accepted event, the instrument records signals from the top and bottom scintillators, Cherenkov counter, the specific ionization (dE/dx), and the transition radiation detector (TRD), as well as details of the particle trajectory through the instrument. Characteristic correlations between these signals lead to the assignment of nuclear charge Z and energy E (or Lorentz factor $\gamma = E/mc^2$). At low energies, below about 10 GeV/amu, the energy measurement comes from the Cherenkov signal, while TRD and dE/dx determine the energy of highly relativistic particles. As an example, we show in Figure 1 the cross-correlation of TRD and dE/dx signals for eight different elements studied in this investigation. The charge Z for each element has been determined from the scintillator signals, and low energy particles are excluded by the additional constraint that the Cherenkov counter must be in saturation (for details see [1]).

The scatter plots show clearly how the signals of dE/dx and TRD are correlated, and increasing with energy along the 45 degree line until, at about 400 GeV/amu, transition radiation sets in and leads to a rapid increase in TRD signal. Hence, the very rare particles, with energies extending well into the 10^3 to 10^4 GeV/amu region, stand out in these scatter plots, and are well separated from low energy background.

2. Absolute Intensities

All accepted events are sorted into energy bins, using the response curves described by Höppner et al. [1]. The energy resolution is different for different energy regions, and generally improves with increasing charge Z because the relative signal fluctuations decrease typically with 1/Z (as can be seen explicitly in the data of figure 1). The width of the energy bins must be commensurate with or larger than the energy resolution of the detector.

In order to obtain absolute particle intensities, we must determine the geometric aperture and the efficiencies of the various analysis cuts on the raw data as accurately as possible. The aperture of the instrument has been

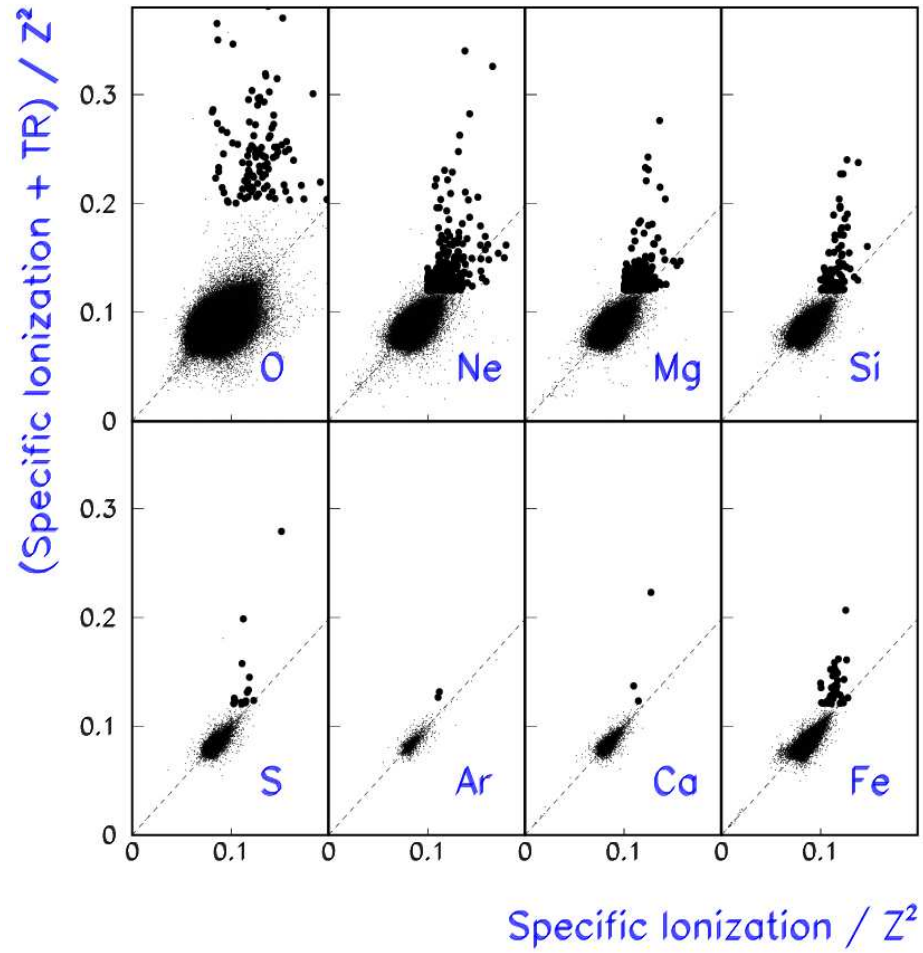

Figure 1. Scatter plot of (TR + dE/dx) against dE/dx for different elements. Note that all signals are normalized by Z^2. The highlighted points represent the highest energy events measured with the TRD. As expected, all the transition radiation events have signals in the dE/dx detector which are well above the minimum ionization level.

determined analytically and verified by a computer simulation which also takes certain "dead" counter areas into account. Instrumental dead-time or data recording inefficiencies were negligible. A number of efficiency factors are derived from the flight data themselves. These include the efficiencies for the charge selection cuts and Cherenkov cuts. Other cuts, for instance the criteria for trajectory selection, require a detailed computer simulation of the entire instrument [2].

Relatively significant, and increasing with Z, are losses of nuclei due to nuclear spallations in the detector material, and due to spallations in the residual atmosphere above the balloon. These can be reliably calculated with known energy-independent cross sections [3], [4]. As an example, Table 1 shows some typical efficiency factors for oxygen and iron nuclei.

Finally, "overlap corrections" in energy must be taken into account, i.e., the number of events in a given energy

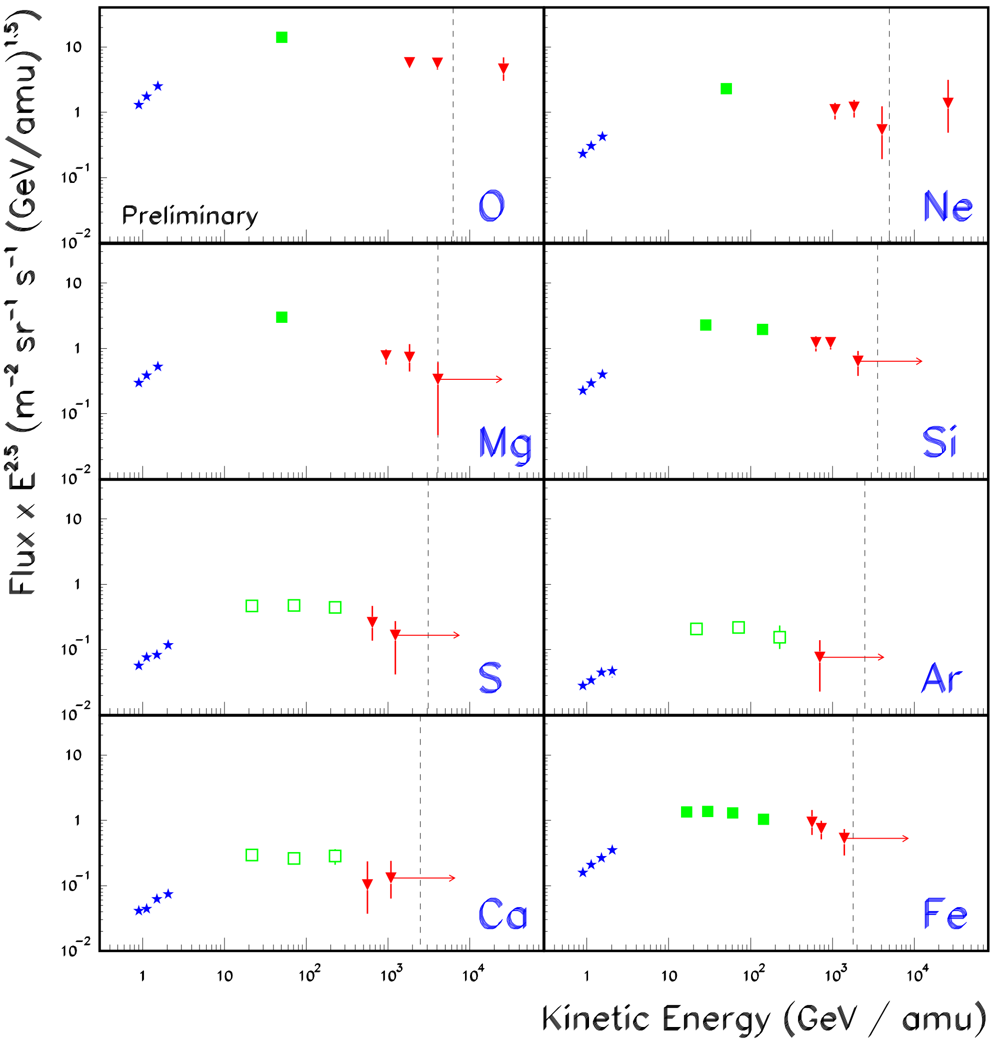

Figure 2. Differential energy spectra for the cosmic ray nuclei O, Ne, Mg, Si, S, Ar, Ca and Fe. Note the fluxes are multiplied by $E^{2.5}$. Energy assignments come from the Cerenkov counter (stars), from the specific ionization (squares), or from TR measurements (triangles). The error bars are statistical. The dashed line indicates a total Energy of 10^{14} eV.

bin that should have been assigned to a neighboring bin due to fluctuations in response. We determine these in an extensive computer model that generates a set of simulated raw data which are then subjected to the same analysis as the real data. We choose the width of the energy bins such that, in general, the overlap corrections are not larger than 10-20%.

Table 1. Efficienies, i.e. fractions of surviving particles, for oxygen and iron.

	Oxygen	**Iron**
Interaction - Atmosphere	82%	72%
Interaction - Instrument	65%	48%
Charge Selection	89%	90%
Tracking Efficiency	95%	95%

3. Resulting Energy Spectra

Figure 2 shows the energy spectra obtained for eight different elemental species. We emphasize that the data analysis is still ongoing and hence, that the spectra shown in the figure must still be regarded as preliminary. The intensities are multiplied with $E^{2.5}$ and are plotted as a function of kinetic energy/amu. For all elements, the dashed line indicates a total energy of 10^{14} eV per particle. We note that for each element, the intensities are given by three groups of data points, low energy data from the Cherenkov counter ($\star$), moderately high energies from the relativistic increase in dE/dx ($\square$), and very high energies from the TRD signals ($\bigtriangledown$). Altogether, the data cover up to four decades in energy, from a few GeV/amu, to more than 10 TeV/amu. In absolute energy, the results for oxygen and neon exceed 10^{14} eV per particle. We emphasize again that all values given are absolute intensities, without any arbitrary normalization. The error bars are statistical, and for the lower energies, are smaller than the size of the symbols in figure 2.

4. Conclusion

We have presented preliminary energy spectra obtained with the TRACER Cosmic Ray detector during a successful long duration balloon campaign in Antarctica 2003. The individual energy spectra for the major elements (O, Ne, Mg, Si and Fe) extend from 0.5 GeV/amu to several 1000 GeV/amu and for S, Ar and Ca from 0.5 GeV/amu to 1000 GeV/amu . These results represent the highest energies for which spectral measurements with individual charge resolution have been reported. In terms of total energy per particle, the TRACER data reach or exceed 10^{14} eV for most of the elements.

These results, while still preliminary, show that the transition radiation technique adopted in TRACER is capable of providing the cosmic-ray composition up to very high energies. The interplay of complementary detection techniques permits an excellent separation of low, moderate and high energy particles, covering over four decades in energy. With some modifications of the TRD system [5], and with sufficient exposure time, such measurements can reach the knee in the cosmic-ray spectrum.

This work has been supported by NASA grants NAG5-5305 and NN04WC08G.

References

[1] Höppner, C. et al., 29th ICRC, Pune (2005) OG1.1
[2] Romero-Wolf, A. et al., 29th ICRC, Pune (2005) OG1.1
[3] Heckman, H.H. et al., Phys Rev C 17:1735-1747, 1978
[4] Westfall, G.D. et al., Phys Rev C 19:1309-1323, 1979
[5] Wakely, S.P. et al, NIM A531, 435, 2004