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# Cosmic Ray Energy Spectra of Primary Nuclei from Oxygen to Iron: Results from the TRACER 2003 LDB Flight

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**Abstract:** The first long-duration balloon flight of TRACER in 2003 provided high-quality measurements of the primary cosmic-ray nuclei over the range oxygen (Z = 8) to iron (Z = 26). The analysis of these measurements is now complete, and we will present the individual energy spectra and absolute intensities of the nuclei O, Ne, Mg, Si, S, Ca, Ar, and Fe. The spectra cover the energy range from 1 GeV/nucleon to more than 10 TeV/nucleon, or in terms of total energy, to several $10^{14}$ eV per particle. We compare our results with those of other recent observations in space and on balloons and notice, in general, good agreement with these data for those regions where overlap exists. We also compare our data with information that has recently been inferred from air shower observations.

## Introduction

TRACER (Transition Radiation Array for Comic Energetic Radiation) is a very large instrument designed to study cosmic ray nuclei above a TeV/nucleon. In 2003 TRACER had a 10 day balloon flight in Antarctica yielding an exposure of 50 m$^2$ steradian days at a residual atmosphere of 3.9 g/cm$^2$. During the flight TRACER collected 50 million cosmic ray nuclei with charge $Z \geq 8$. The analysis of this data-set is now complete and we present here the energy spectra for eight elements O, Ne, Mg, Si, S, Ar, Ca and Fe. The results cover over four decades in energy and are given as absolute intensities, without arbitrary normalizations.

## Absolute Intensities

Depending on the method of energy assignment, each event that passes the data analysis cuts is classified either as a *Cerenkov Event*, *dE/dx Event* or *Transition Radiation Event*. These events are sorted into energy bins, using the response curves described by Müller (these proceedings [1]). The width of each energy bin is commensurate with the energy resolution and varies with energy E and charge Z. As the relative intrinsic signal fluctuations decrease proportional to 1/Z, the energy resolution improves with increasing charge. To convert from the number of events $N_i$ in a particular energy bin $\Delta E$ to an absolute differential flux $\mathrm{d}N_i/\mathrm{d}E$ at the top of the atmosphere one must compute the exposure factor, effective aperture, efficiency of the cuts and unfold the instrument response :

$$\frac{\mathrm{d}N_i}{\mathrm{d}E} = \frac{N_i}{\Delta E} \cdot \frac{1}{T_l} \cdot \frac{1}{\varepsilon_i} \cdot \frac{1}{A_i} \cdot C_i \quad (1)$$

with $T_l$ the live-time, $\varepsilon_i$ the efficiency of analysis cuts, $A_i$ the effective aperture and $C_i$ the "overlap correction" due to misidentified events from neighbouring bins. The effective aperture is :

$$A_i = A \cdot 2\pi \int_{\theta=0}^{\pi/2} P_I(\theta) P_D(\theta) cos\theta \, \mathrm{d}(cos\theta) \quad (2)$$

with A the area of the detector (2.06 m $\times$ 2.06m), $P_I(\theta)$ the probability of survival in the atmosphere and the instrument as a function of zenith angle $\theta$, $P_D(\theta)$ the probability that a particle passing through the instrument will be detected. The Overlap corrections are determined with Monte Carlo

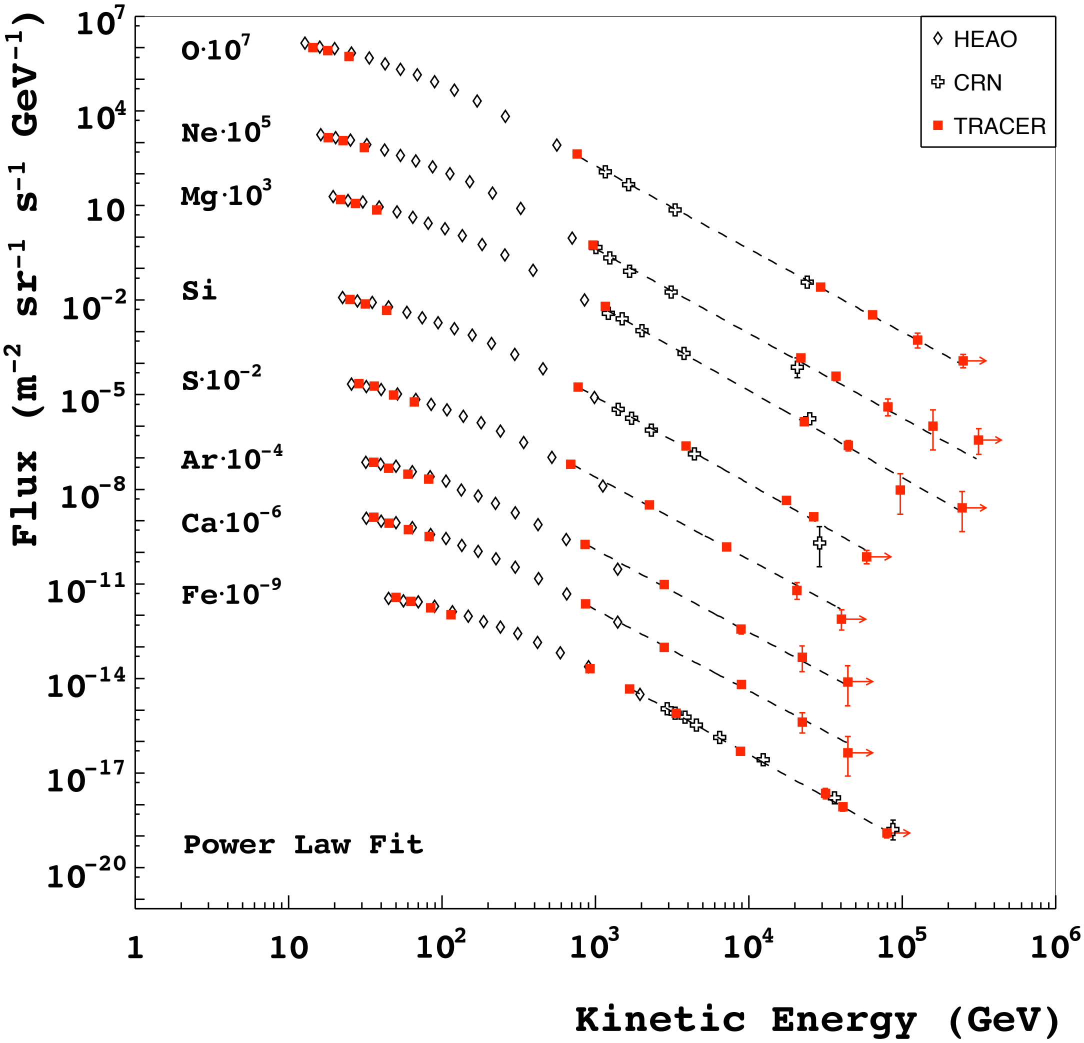


Figure 1: Differential energy spectra for the cosmic ray nuclei : O, Ne, Mg, Si, S, Ar, Ca and Fe. Results from the TRACER 2003 Antarctica flight are indicated by the red squares. Existing data from the HEAO-3 experiment (open diamonds) [2] and the CRN experiment (open crosses) [3] are shown for comparison. The dashed line represents an independent power-law fit to each spectrum above 20 GeV/nucleon.

simulations and are typically $\leq 20\%$ (i.e. $0.8 \leq C_i \leq 1.2$). An example of efficiencies etc is given for oxygen and iron in Table 1 of Müller [1]. The energy assigned for each bin is defined as :

$$E = \frac{1}{E_2 - E_1} \cdot \frac{1}{1-\alpha} \cdot (E_2^{1-\alpha} - E_1^{1-\alpha})^{-1/\alpha} \quad (3)$$

where $\alpha$ is the power-law exponent of the differential energy spectrum. The method is discussed in detail by Lafferty and Wyatt [4].

## Resulting Energy Spectrum

The energy spectra, in terms of absolute intensities, for the elements O, Ne, Mg, Si, S, Ar, Ca and Fe are presented in Figure 1. We note the large range in intensity (ten decades) and particle energy (four decades) covered by TRACER. This has been achieved by three complementary measurements in one detector : the Cerenkov counter ($\sim 10^{11}$ eV), the relativistic rise of the ionization signal in gas ($\sim 10^{11} - 10^{13}$ eV) and the Transition Radiation Detector ($> 10^{13}$ eV) [1]. Data from the TRACER 2003 flight are indicated by the red squares. For clarity the intensity of each element is multiplied by a factor shown on the left. Existing data from measurements in space with HEAO-3 (open diamonds) and CRN (open crosses) are shown for comparison. As can be seen, the energy spectra for O, Ne, Mg and Fe extend up to and beyond $10^{14}$ eV. No evidence for any significant change in spectral slope is evident at the highest energies. The energy spectrum of each element (from TRACER and CRN) is fit to a power law above 20 GeV/nucleon. The resulting spectral indices (Figure 2) are remarkably similar, with an average of 2.65.

Figure 3 compares the TRACER results for iron with results from a number of other investigations. Below $10^{12}$ eV we show results from HEAO-3 [2] and at higher energies from CRN [3] on the space shuttle and from the ATIC-2 [5] and RUNJOB balloon experiments [6]. The dashed line represents a power-law fit with an exponent of -2.7 and describes the data well above $10^{12}$ eV. Figure 3 also illustrates the variety of detection techniques used in measuring the energy of heavy nuclei. Within

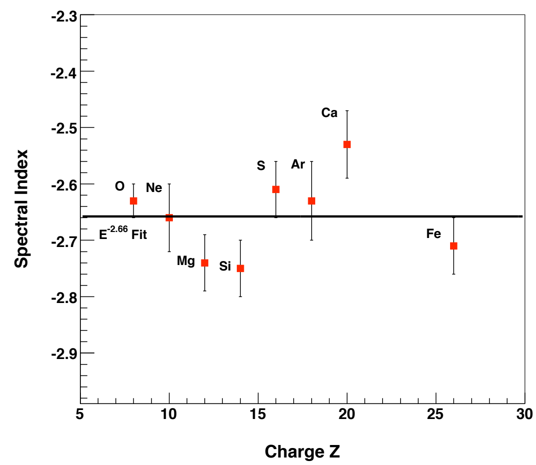


Figure 2: Spectral indices of a best power-law fit to the combined TRACER and CRN data above 20 GeV/nucleon. The line indicates the an average spectral fit of $E^{-2.65}$.

the statistical uncertainties (which in some measurements are quite large), the data indicate fairly consistent results. The Transition Radiation technique of TRACER can, in principle, provide measurements with energies up to around $10^{15}$ eV. The range of the current results is limited by the exposure available. Also presented in Figure 3 are recent results from the ground based HESS Imaging Air Cerenkov Telescope using the Direct Cerenkov Technique (green triangles). These results are the first examples of a new technique for measurements from the ground [7]. Two flux values are presented for each energy indicating ambiguities from different interaction models [8]. Again, these data are consistent with TRACER.

## Comparison with Air-shower Data

Data for oxygen and iron for TRACER are compared in Figure 4 with spectra derived from indirect observations of the EAS-TOP collaboration [9], and of the KASCADE group for two different nucleus-nucleus interaction models [10]. However, these groups do not report results for individual elements: the fluxes for the "CNO group" probably have about twice the intensity than oxygen alone,

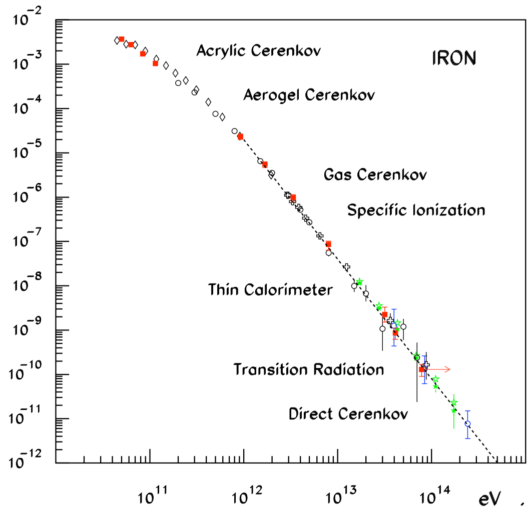


Figure 3: Iron energy spectrum above $10^{10}$eV per particle in units of $m^2$ $ster^{-1}$ $s^{-1}$, highlighting the complementarity between detection techniques. TRACER (red squares), HEAO-3 [2] (black diamonds), CRN [3] (black crosses), ATIC-2 [5] (black open circles), RUNJOB [6] (blue open circles) and HESS [8] (green stars).

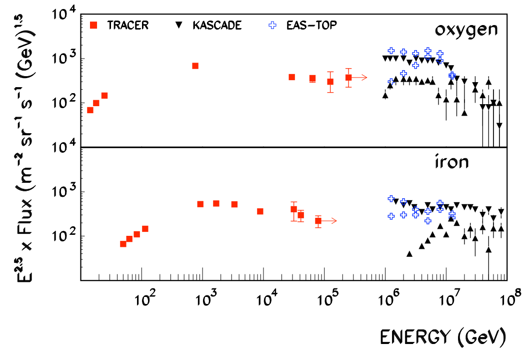


Figure 4: Energy Spectra from TRACER and from the interpretation of air shower data of KASCADE (for two different interaction models) and of EAS-TOP (two data points for each energy are given, representing upper and lower limits). The spectra are for oxygen and for iron for TRACER, but for the "CNO-group" and the "Fe-group" for the other observations.

while the "iron group" probably is dominated by iron. Our results do not yet overlap with the energy region of the air shower data, but the gap is becoming smaller, in particular for oxygen. Additional measurements will indeed lead to significant constraints on the air shower interpretations.

## Conclusion

The TRACER 2003 data represent the most detailed measurements to date for heavy nuclei above a TeV/nucleon with single charge resolution. While the results do not reveal any surprising features in the cosmic ray energy spectra at high energies, they begin to provide stringent constraints on the conventional models on galactic propagation. The analysis of the TRACER results in the context of these models is discussed in these proceedings (Ave et al. [11]).

We acknowledge support as summarized in Müller et al [1].

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