Composition and energy spectra of cosmic-ray nuclei at high energies

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***Abstract*. The TRACER ("Transition Radiation Array for Cosmic Energetic Radiation") instrument was designed for direct composition measurements up to the energy regime where air shower experiments begin to provide indirect information. The first LDB flight in 2003 over Antarctica provided the energy spectra of primary nuclei from oxygen (Z=8) to iron (Z=26) up to energies in excess of 10^{14} eV per particle. For the second flight in 2006 from Kiruna (Sweden), the dynamic range of the measurement was extended to include the light elements from boron (Z=5) to nitrogen (Z=7). We will discuss the analysis of these new data and present preliminary results.**

***Keywords*: cosmic ray composition, propagation, balloon**

I. INTRODUCTION

In 2003, TRACER conducted its first long duration balloon flight (LDB) in Antarctica. The measurement included eight primary cosmic-ray species from oxygen to iron up to energies of 10^5 GeV and even higher for the more abundant nuclei. The observed energy spectra are shown in figure 1. More details on this measurement are given in [1].

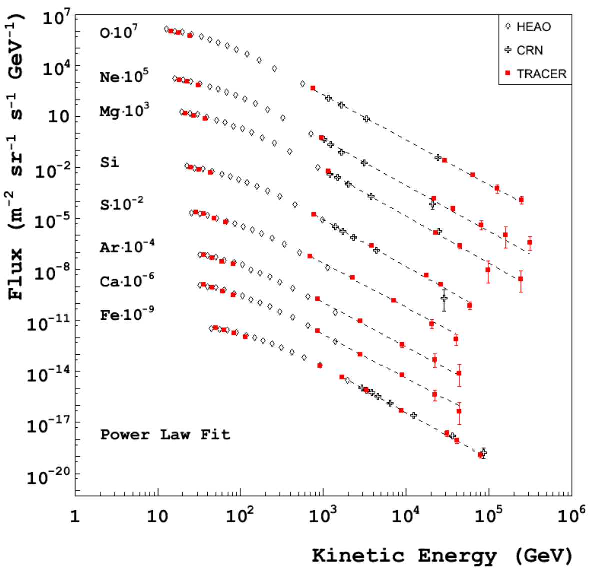

Fig. 1. Energy spectra measured with TRACER in 2003.

A detailed analysis of the data from this first flight is given in [2]. A leaky box model was used to find source abundances, a common spectral index α at the source, and a residual pathlength Λ_0 to which the escape pathlength asymptotically converges at high energies.

The reconstructed source abundances of the studied elements show good agreement with previous experiments at low energy, with similar correlations with volatility and first ionization potential. The results for α and Λ_0 suggest a soft source spectrum ($\alpha \approx -2.4$) with a non-zero residual pathlength ($\Lambda_0 \approx 0.3$ g/cm^2). However, the results for Λ_0 remain quite uncertain because of limited statistics. See also [3].

A further constraint on the residual pathlength is needed, which will also reduce the uncertainty in the source spectral index. This can be achieved by a measurement of the abundance ratio of secondary to primary cosmic-ray nuclei at high energies, e.g. boron to carbon. The TRACER instrument was upgraded and flown to accomplish such a measurement.

II. UPGRADES AND LDB FLIGHT 2006

For the 2006 flight, an additional acrylic Cerenkov detector at the top of the instrument was included. With this, the detector layout is as shown in figure 2. Between two identical sets of Cerenkov and scintillation detectors at the top and bottom of TRACER are 1600 single-wire proportional tubes, arranged in 16 layers. The upper eight layers (dE/dX array) measure energy loss of charged particles in gas. The lower eight layers (TRD), with radiator material interspaced, measure the energy loss plus transition radiation (TR). TRACER has an area of 2×2 m^2 and a total aperture of 5 m^2 sr.

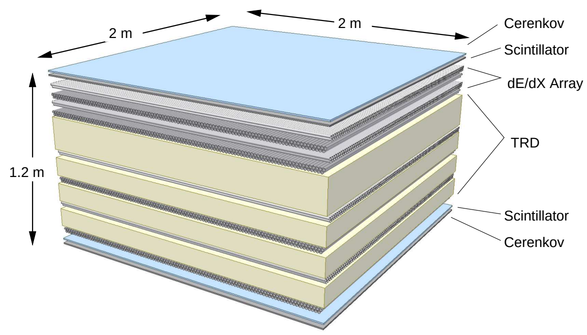

Fig. 2. Schematic illustration of TRACER.

For the 2006 flight, all proportional tubes were equipped with a dual gain output that provides a dynamic range of about 13,000 channels, enough to resolve

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signals of elements from boron to iron. Also, four times as much Xe gas was used for the second LDB flight (i.e. a 95/5 mixture of Xe/CH_4 rather than 25/75 Xe/CH_4 as in 2003).

TRACER was launched in July 2006 from Kiruna (Sweden). The flight was terminated over Canada after only 5 days of flight because a lack of international agreements precluded a complete circumpolar trajectory. The detector functioned well and collected about 30 million cosmic-ray events in its 60 hour lifetime. The residual atmosphere above TRACER was 3.5 g/cm^2.

III. Data Analysis

After extracting tracking information from the perpendicular layers of proportional tubes, the charge and energy of the nucleus of each event has to be reconstructed.

The charge analysis relies on the cross correlation of scintillator and Cerenkov detector signals. There elements align themselves on tracks of constant charge that are well separated. A charge histogram can be generated by summing along these tracks. For one combination of scintillator/Cerenkov detectors the charge resolution is about $0.25e$ for boron and about $0.5e$ for iron. This is improved when both detector combinations at the top and the bottom of the instrument are combined. A 2-dimensional charge histogram of the lighter charges is shown in figure 3. The elements are clearly resolved along the diagonal (note the logarithmic color scale).

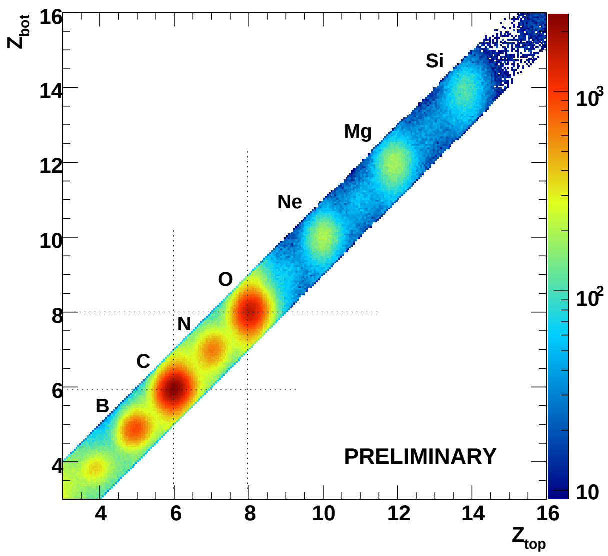

Fig. 3. Charge correlation of top and bottom charges. Interacting nuclei have been removed. The dotted lines indicate the positions of carbon and oxygen.

An energy measurement over more than 4 orders of magnitude is achieved by combining the energy responses of subdetectors. Figure 4 shows the energy responses of the Cerenkov detector, dE/dX array, and TRD. The ambiguity of a low energy dE/dX signal and a high energy TR signal is broken by the Cerenkov detector signal. The energy resolution of the Cerenkov detector (used for low energy events, $\gamma < 10$) and of the TRD (used for high energy events, $\gamma > 400$) is very good; for $Z = 12$, typical values are about 6% and 15% respectively.

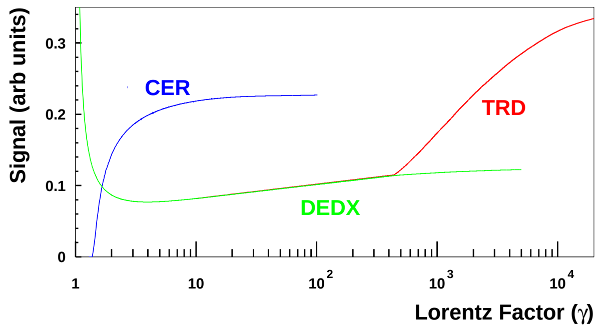

Fig. 4. Response functions of TRACER subdetectors.

In the energy range $10 < \gamma < 400$, the energy measurement relies on the relativistic rise of the energy loss of charged particles in gas. This rise is shallow and can only be used when the signal fluctuations are small. This is especially true for the lighter elements. With the proportional tubes filled with four times as much Xe gas as in the first flight, the statistical signal fluctuations are reduced and the energy resolution greatly improved as seen in figure 5. This improvement allows for the measurement of energy for boron and carbon nuclei within the range of the relativistic rise.

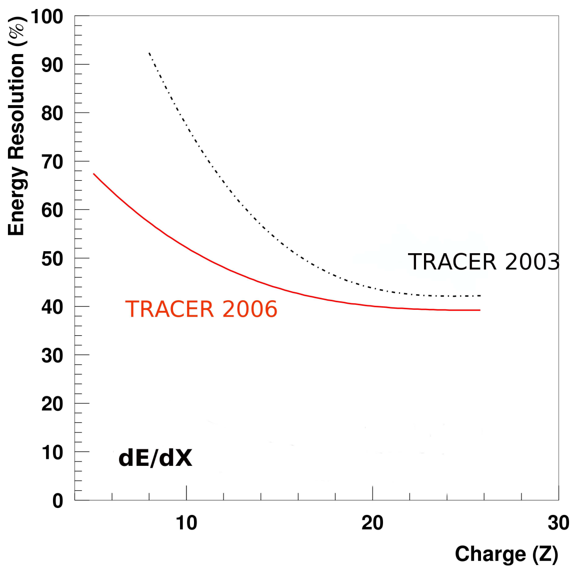

Fig. 5. Measured energy resolution of the dE/dX detector for 2003 (black) and for the improved 2006 configuration (red).

IV. Preliminary Results

To assign events to energy bins and to identify high energy TR events, the correlation of dE/dX-array and TRD signals is used. Figure 6 shows this correlation for iron and boron. The large population around minimum ionizing extends along the diagonal as the energy, and thus the signal, increases along the relativistic rise. When the energy of a nucleus is above 400 GeV/amu, TR is produced and the event can be clearly identified above the diagonal. The corresponding iron spectrum is shown in figure 7. The spectrum shows good agreement between this work and the results from TRACER 2003 as well as with previous space experiments. The boron correlation plot also clearly shows the effect of the relativistic rise. Despite the lower abundance of boron, there is one possible TR event, which could have an energy of multiple TeV/amu.

Future work is required to reduce possible systematic uncertainties, and to further reduce signal fluctuations. We expect to show energy spectra for carbon and boron at the conference.

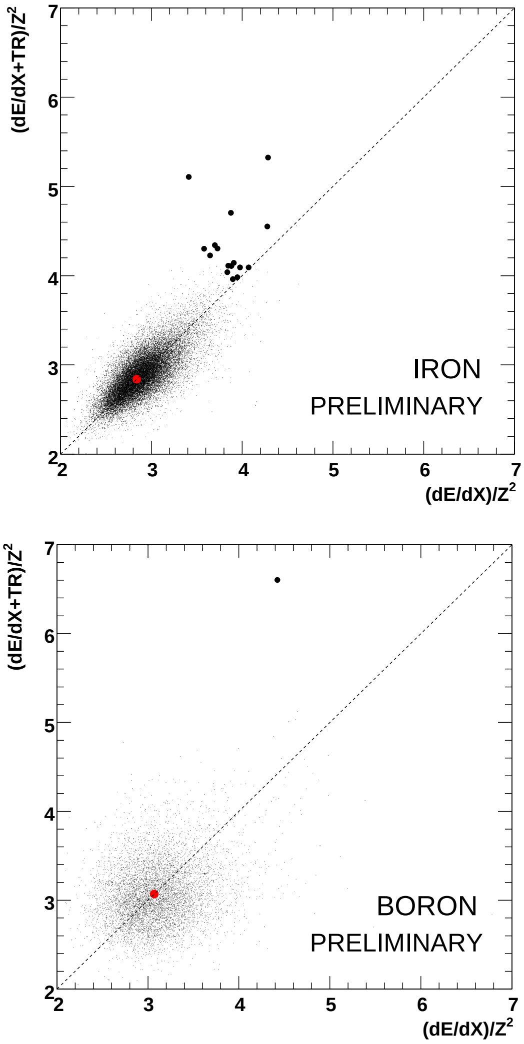

Fig. 6. Cross correlation of dE/dX and dE/dX+TR signals for iron and boron. The sparser and wider distribution of boron reflects larger fluctuations and harder selection cuts. Minimum ionizing is marked by a red dot.

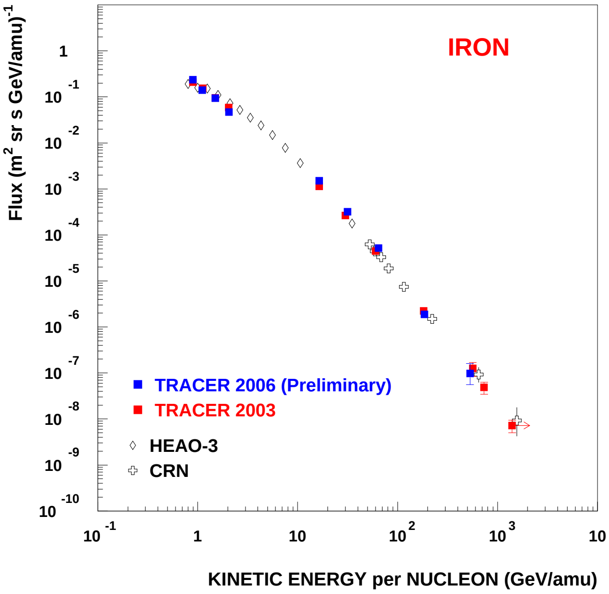

Fig. 7. Iron spectra of TRACER 2006 and 2003 together with space mission data.

V. CONCLUSION

First results from the 2006 LDB flight of TRACER show that the upgraded instrument operated as expected and that a measurement of the boron to carbon abundance ratio up to hundreds of GeV/amu is possible with the current dataset. More results will be presented at the conference.

Despite this successful measurement, more statistics will be needed. Future detectors should also be able to resolve the sub-iron elements in order to gain more detailed information on the propagation of galactic cosmic rays. To this end, a new detector based on the TRACER design is proposed in [4].

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