New measurements of the composition and energy spectra of cosmic-ray nuclei with TRACER

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Abstract: The TRACER cosmic-ray detector has been flown in two long-duration balloon flights, in Antarctica in 2003, and in the Northern hemisphere from Sweden to Canada in 2006. TRACER is a very large counter system, relying entirely on electro-magnetic interactions to determine the charge Z and the Lorentz-factor $\gamma = E/mc^2$ of cosmic-ray nuclei. The instrumentation includes a large array of proportional tubes that measures the ionization loss in gas, and the transition radiation signal produced by highly relativistic nuclei in plastic-fiber radiators, and thus, reaches energies up to nearly 10^4 GeV per nucleon. For the flight in 2003, the measurement covered the heavier nuclei from oxygen ($Z = 8$) to iron ($Z = 26$). Major modifications to the detection system were made for the 2006 flight in order to also include the lighter nuclei from boron ($Z = 5$) to nitrogen ($Z = 7$). We shall present and discuss the final results combined from these flights: the individual energy spectra and relative abundances of the elements from boron to iron. In particular, we shall present new results on the energy spectra of the secondary element boron and its primary parent carbon up to 10^3 GeV per nucleon.

Keywords: balloon, cosmic-ray energy spectra, boron

1 Introduction

The TRACER ("Transition Radiation Array for Cosmic Energetic Radiation") instrument was developed for direct measurements of the energy spectra of cosmic-ray nuclei extending into the high-energy region, i.e. energies around and above 10^{12} eV amu^{-1} in long-duration balloon (LDB) flights. TRACER was designed and constructed at the University of Chicago, utilizing the heritage of the CRN detector flown on the Space Shuttle [5].

TRACER had a two-week circum-polar LDB flight in Antarctica in 2003 (LDB1). The results from this flight [2] provide the individual energy spectra of the major primary cosmic-ray nuclei from oxygen ($Z = 8$) to iron ($Z = 26$). Subsequently, the instrument underwent a significant upgrade in order to include the light nuclei below oxygen in the measurement. The upgrade enhanced the charge resolution, as well as the energy resolution at high energies, especially for the light elements. A second balloon flight was conducted from Kiruna (Sweden) to Northern Canada in 2006 (LDB2).

Measuring the energy spectra of light elements is crucial for the understanding of cosmic-ray propagation and acceleration. The propagation path length of cosmic rays can be determined from the energy spectra of secondary nuclei, i.e. those elements that are produced exclusively by interstellar spallation. This group includes the light element boron, which is studied by LDB2 of TRACER.

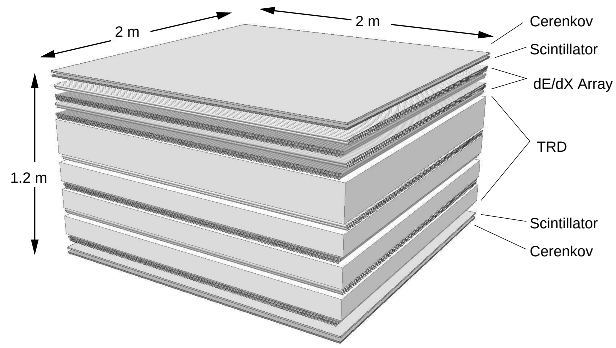

Figure 1: Schematic view of the detector elements of TRACER.

In the following, we will present the measured energy spectra of LDB2 and describe the combined data set from LDB1 and LDB2.

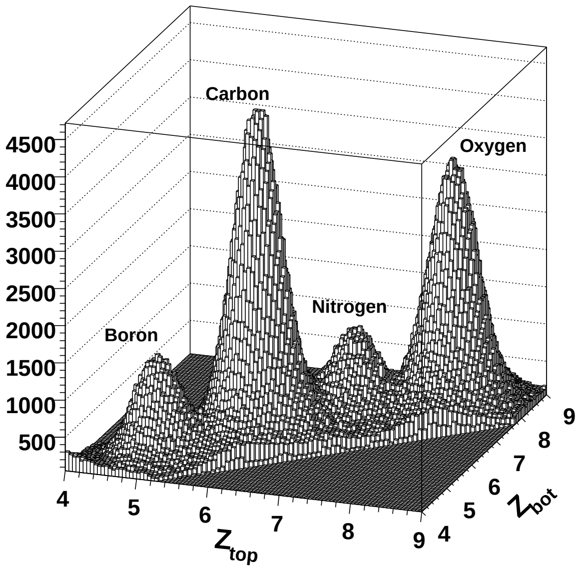

Figure 2: Charge histogram for the light elements.

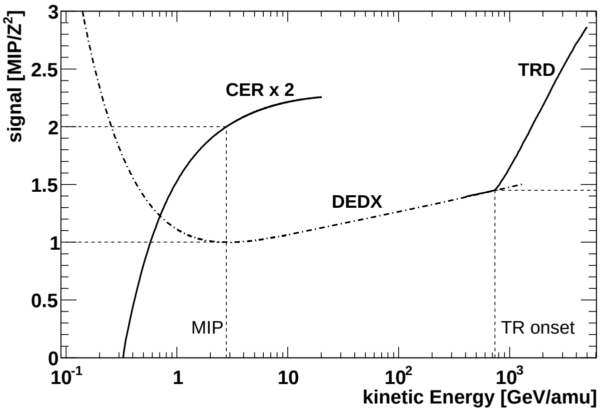

Figure 3: Response functions, in units of signal at minimum ionizing energy (MIP) normalized by Z^2, of sub-detectors used for energy measurements. The dashed lines indicate the signals at minimum ionizing energy and TR onset.

2 The Detector and the Measurement

The TRACER instrument employs light-weight materials to determine charge and energy of cosmic rays exclusively via electro-magnetic interactions. In contrast to calorimetric measurement, a nuclear interaction is not required to occur, and, therefore, TRACER exhibits the largest geometric factor (~5 m^2 sr) of all current instruments. It represents a combination of plastic scintillator sheets, acrylic Čerenkov counters, and single-wire proportional tubes. A schematic drawing of TRACER is shown in Figure 1.

The arrays of gas-filled, single-wire proportional tubes are arranged in double-layers in densest packing and are alternately oriented in two orthogonal directions. The four upper double layers measure the ionization energy loss ("dE/dx"). Each of the four remaining layers is located below a radiator layer and measures ionization loss with transition radiation superimposed ("dE/dx + TR").

For each cosmic-ray nucleus that traverses the instrument, the nuclear charge Z and the energy E (or the Lorentz-factor $\gamma = E/mc^2$) are determined. The charge is obtained from the signals of the Čerenkov-scintillator combination, utilizing the fact that electromagnetic interactions scale with Z^2, while the energy dependence of these two signals is different. The resulting charge histogram for the light elements boron, carbon, nitrogen, and oxygen is shown in Figure 2.

The energy measurement of TRACER depends on the energy response of the Čerenkov detector signal, the magnitude of the relativistic increase in specific ionization in the gas-proportional tubes, and on the energy dependence of the transition radiation (TR) signal. The characteristic response curves are shown in Figure 3. The very rapid rise of the Čerenkov signal permits an accurate measurement at low energies (~0.5 to 3 GeV amu^{-1}). The much slower rise of the ionization signal allows for an energy determination in the range of ~ 10 to a few hundred GeV amu^{-1}, if the magnitude of this rise is larger than the level of fluctuations in the signals. Finally, the highest energies can be rather precisely determined from the rapid increase of the TR intensity as function of energy. Because of the steeply falling energy spectrum of cosmic rays, the measurements at high energies are limited by counting statistics and not by saturation of the detector response.

3 Energy Spectra of Cosmic Rays

3.1 Primary Elements C, O, and Fe

The differential energy spectra for iron, oxygen, and carbon are given in terms of absolute intensities on top of the atmosphere in Figure 4. The figure includes previously published data for comparison, and the energy spectra are shown multiplied by $E^{2.65}$ for clarity. The measurement of LDB2 reaches an energy of 2 TeV amu^{-1}. While the flight duration of LDB2 was shorter than for LDB1, the measured energy spectra agree well for the two flights [3], except at low energy (at about 1 GeV amu^{-1}), where the intensities from LDB2 are consistently higher compared to previous measurements. This can be attributed to the different solar modulation of low-energy cosmic rays at the time of the flight. Where overlap exists, the TRACER results are also in good agreement with measurements from HEAO [4], CRN [6], ATIC [11], and CREAM [1], within the sizable uncertainties quoted.

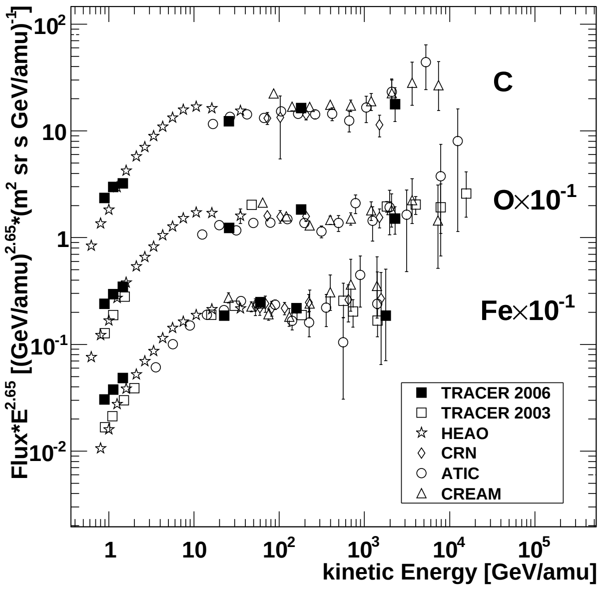

Figure 4: Differential energy spectra of carbon, oxygen, and iron (top to bottom). The spectra are multiplied by $E^{2.65}$, as well as divided by 10 for oxygen and iron. For comparison, results from HEAO [4], CRN [6], ATIC [11], and CREAM [1] are shown. The error bars are statistical.

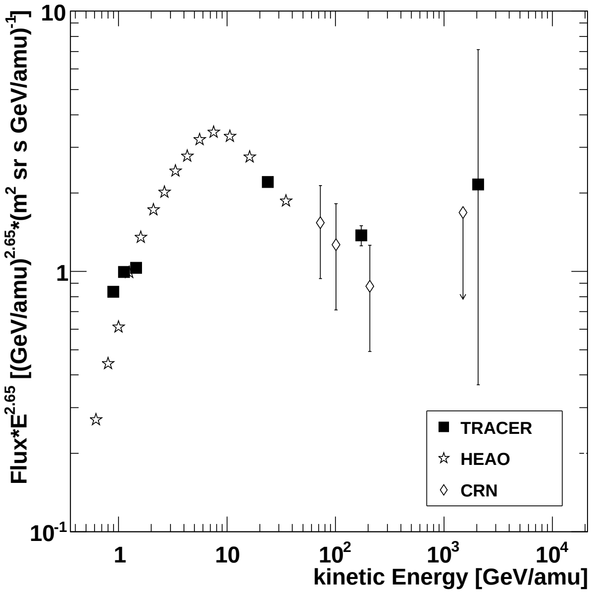

Figure 5: Differential energy spectrum of boron. The spectrum is multiplied by $E^{2.65}$. For comparison, results from HEAO [4] and CRN [12] are shown. The error bars are statistical.

3.2 The secondary Element Boron

Boron is a secondary element produced by spallation mainly of carbon and oxygen during propagation through the Galaxy. The parent nuclei of boron are much more abundant than boron itself. Therefore, two additional considerations have been taken into account when deriving the energy spectrum of boron: (1) contamination of the high-energy boron sample with a small admixture of carbon nuclei (~ 0.6%), and (2) the contribution of boron nuclei generated in the residual atmosphere above the balloon (see also [7]).

The energy spectrum of boron is shown in Figure 5. There are only two measurements besides TRACER that report absolute intensities at relativistic energies: HEAO-3 [4] and CRN [12], but none of these extends into the TeV amu^{-1} region. The present measurement of the absolute boron energy spectrum up to 2 TeV amu^{-1} includes the highest energy boron nucleus ever recorded. Agreement between the present work and previous measurements can be noted within the quoted error limits, and in the energy region where overlap exists. It can also be seen, that the boron spectrum of Figure 5 at high energies is clearly steeper than the spectra of the primary elements (note that the boron spectrum is also scaled by $E^{2.65}$ in the figure).

3.3 The combined Data

We have described a new measurement of the energy spectra of highly relativistic cosmic-ray nuclei. The TRACER instrument had previously (LDB1) provided measurements of the heavier nuclei from oxygen to iron ($Z = 8$ to 26). The most recent flight (LDB2 in 2006) includes the lighter nuclei and covers the region from boron to iron ($Z = 5$ to 26). A compilation of all present results from the two LDB flights of TRACER is given in Figure 6.

Overall the TRACER measurement now spans elements from boron to iron over more than four decades of total energy from below 10 GeV to above 100 TeV for the more abundant species. The measurements have significantly extended previous data. The observed intensities of the primary elements feature a spectral index of 2.67 ± 0.05 above 20 GeV amu^{-1}. A more detailed study of the LDB1 results [3] has suggested a soft spectral index for the energy spectrum at the source. A detailed analysis of the current data, including the secondary element boron, confirms and extends these findings. This will be discussed at this conference by Obermeier *et al.* [10].

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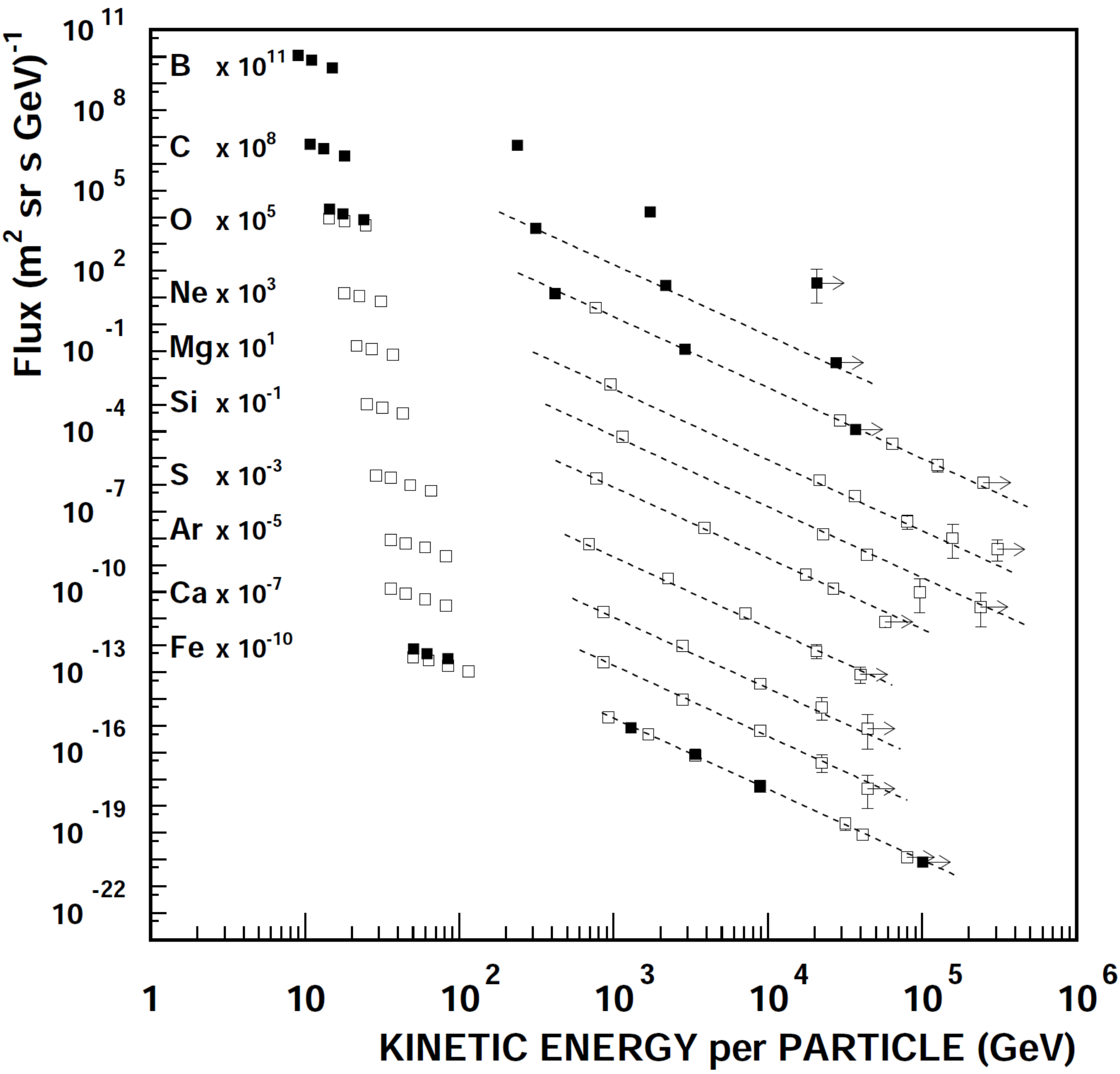

Figure 6: Compilation of the differential energy spectra measured by TRACER in LDB1 [2] (open symbols) and LDB2 [8] (filled symbols).

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