Definitive measurements of secondary production of cosmic-ray nuclei: The next step

D. Müller*, **P. J. Boyle**[1]*, **S. Coutu**†, **T. Hams**‡, **J. Marshall***, **J. Mitchell**‡, **A. Obermeier***

*Enrico Fermi Institute, University of Chicago, Chicago, Illinois, USA
†Pennsylvania State University, College Station, Pennsylvania, USA
‡NASA Goddard Space Flight Center, Greenbelt, Maryland, USA

***Abstract*. Detailed knowledge of the energy dependence of the galactic propagation of cosmic rays is necessary to understand their energy spectra and acceleration at the sources. A key observation is the measurement of the relative abundances of secondary nuclei, such as the light nuclei below carbon and the sub-iron nuclei, and of the partially secondary odd-Z nuclei. Currently available data are very limited at high energies. An extension of the measurements into the TeV-range is crucial, but entails difficult observational requirements. We discuss a detector arrangement which would employ a large-area transition radiation detector system, such as successfully used on the TRACER payload, combined with high-resolution acrylic and aerogel Cherenkov counters. We demonstrate the capabilities of this system with realistic simulations.**

***Keywords*: Secondary cosmic rays, future instrumentation**

I. Introduction

Cosmic rays below the "knee" (10^{15} eV per particle) are commonly assumed to be generated in Galactic sources. While propagating through the interstellar medium (ISM), their composition and energy spectra undergo characteristic changes. The propagation processes are commonly described in a continuity equation which contains many parameters that are poorly known, and simplifications must be made to obtain solutions. The most popular approximation, the "leaky box" model for cosmic-ray nuclei, requires the knowledge of the "propagation pathlength" $\Lambda(E)$ which quantifies the diffusion through the ISM (and which may depend on the cosmic-ray energy E), the spallation pathlength $\Lambda_s(A)$ which is the scale length for the production of secondary nuclei (and which decreases with mass number A), the production rate at the source (typically a power law in energy, $E^{-\alpha}$ or rigidity, $R^{-\alpha}$), and the knowledge of nuclear interaction cross sections. An analysis of measured data in the context of this model has been performed for the energy spectra of the heavier primary cosmic-ray nuclei observed with the TRACER detector ([1], [2]). However, these measurements did not include detailed information on secondary nuclei over a wide range of energies. Here we discuss the observational challenge of such measurements.

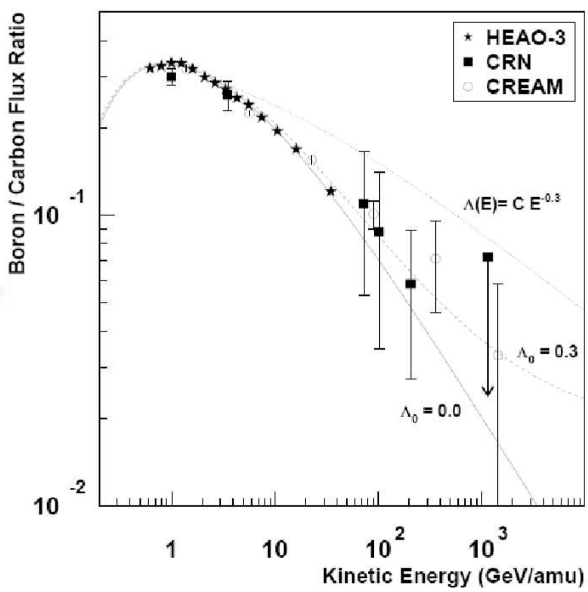

Fig. 1. Measurements of the B/C abundance ratio vs. energy. The curves correspond to $\Lambda \propto E^{-0.6}$ and zero or 0.3 g/cm^2 residual, or to $\Lambda \propto E^{-0.3}$ with zero residual.

II. Current Data

The observed energy spectra of individual cosmic-ray nuclei are steeper (softer) than the spectra predicted (with spectral indices α just slightly larger than 2.0) by the shock-acceleration model. This behavior is consistent with measured data that show that the propagation pathlength Λ decreases with energy . $\Lambda(E)$ is determined from the abundances of secondary nuclei relative to those of their primary parents, but currently available data are quite limited at high energies. Figure 1 shows high-energy results for the B/C abundance ratio from measurements in space ([3], [4]), and from a recent CREAM measurement [5]. The data are consistent with an $E^{-0.6}$ energy-dependence, but at energies above the 100 GeN/nucleon region, the uncertainties are too large to provide strong constraints on $\Lambda(E)$. Few data for other secondary nuclei, such as Li and Be, or the elements just below Fe, are currently available at high energies. Yet, it is crucial that the energy dependence of Λ be investigated with much greater detail, and that

[1]currently at McGill University, Montreal, Canada

the measurements extend at least into the TeV/nucleon region. Even if the $E^{-0.6}$ behavior applies at lower energies, it may very well be that the decrease of Λ is arrested by a fixed residual pathlength Λ_0 such that $\Lambda(E) = C \cdot E^{-0.6} + \Lambda_0$ [2]. An accurate knowledge of $\Lambda(E)$ which applies to all nuclear species, is essential to use the ambient cosmic-ray measurements near earth for a determination of the spectral shapes and relative abundances that are characteristic for the sources.

Such measurements represent a severe observational challenge: First, a detector is required that has superb charge resolution (< 0.2 charge units) for all individual elements from Li to Fe. Second, accurate energy measurements must be made over the range of three to four decades above 10 GeV/nucleon. Third, the detector must have sufficient size and observation time to permit an exposure factor of the order of several hundred m^2 sr days. Even then, the maximum achievable energy coverage depends on how fast Λ declines with energy. Finally, for balloon-borne measurements, the fraction of secondary nuclei produced in the residual atmosphere must be reliably determined.

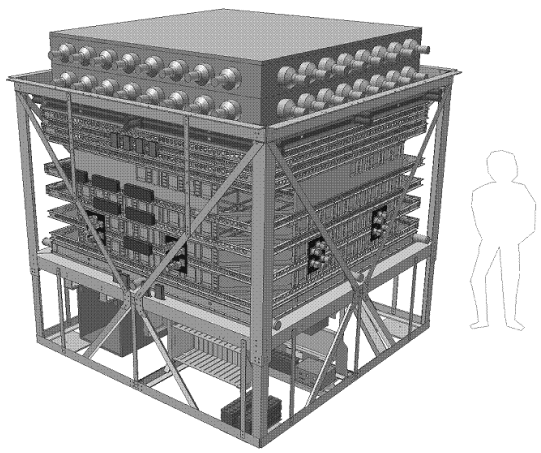

Fig. 2. Combination of TRACER with two Cherenkov counters in light-integration boxes.

III. The Detector Concept

Energy measurements of cosmic-ray particles that are based on electromagnetic interactions are an obvious approach to obtain cosmic-ray detectors with an attractive area-to-weight ratio. This approach has been implemented with the TRACER instrument ([6], [7]) for long-duration balloon flight. This instrument uses a combination of Cherenkov, ionization, and transition radiation (TR) detectors to measure particle energies (or Lorentz-factors) from a few to 10,000 GeV/nucleon, and it achieves a record geometric factor of 5 m^2 sr without exceeding the weight constraints of balloons. TRACER has demonstrated in two balloon flights its capability for accurate energy measurements. Most importantly, TRACER measures independently the ionization energy loss in gas (including its relativistic rise with energy) for all energies, and the transition radiation signal that might be superimposed to the ionization loss signal in the TR detector. This unique feature makes it possible to select the very rare particles at the highest energies from the much larger total particle flux.

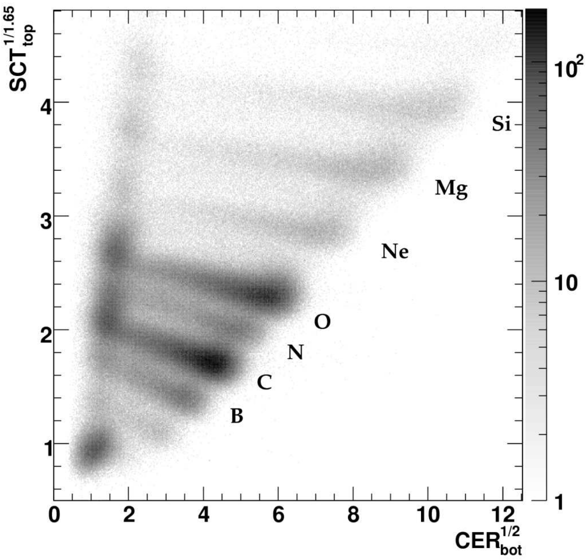

Fig. 3. Scatter plot of plastic scintillator signals vs. acrylic Cherenkov signals. Data from TRACER 2006 flight.

TRACER has determined the energy spectra for the major primary nuclei O to Fe. The second balloon flight also has provided some information on the relative intensity of B, albeit mostly below the TeV region due to the relatively short duration of the flight. The major design goal of TRACER were measurements of the primary source nuclei. To optimize the charge resolution for comprehensive measurements of primary, secondary, and partially secondary nuclei, the instrument should be combined with an upgraded Cherenkov counter system as shown in Figure 2. We call this combination TRACER-PLUS. To understand the figure, we must recall the detector configuration of the current TRACER instrument which contains on top a double layer of a plastic scintillator and an acrylic Cherenkov counter, both read out via wavelength shifter bars. These counters identify cosmic ray nuclei as shown in the scatter plot of Figure 3. The widths of the "tracks" in this plot illustrate the limitations in the charge resolution obtained with this pair of counters: the widening and "turn-up" of the scintillator signal is due to contributions of δ-rays in the minimum-ionization region, and the Cherenkov signal fluctuations are caused by photo-electron statistics (due to the inefficient wavelength-shifter readout, the light yield is only 2-3 photoelectrons per Z^2 in Cherenkov saturation). Thus, a dramatic improvement (about a factor of 10 in photoelectron-yield) can be obtained if the Cherenkov counter is placed in a light-integration box. Second, one should add an Aerogel

Cherenkov counter to the detector system, again in a light-integrating box. Figure 2 illustrates how these two boxes, including photomultipliers, could be combined with the existing TRACER configuration. The aerogel counter, with a threshold Lorentz-factor of 3.6 (for n=1.04) will provide energy-dependent signals well above the minimum ionization energy level (where the signals in Figure 3 saturate), and the elemental charge Z of cosmic rays can be obtained with excellent resolution just from the cross-correlation of the signals of the two Cherenkov counters, as indicated in a realistic simulation in Figure 4. In contrast to scintillators, the Cherenkov response scales strictly with Z^2. Hence, good charge resolution is achieved up to the highest charges of concern. The practicality of this approach has been demonstrated in a very similar configuration used for the TIGER instrument [8].

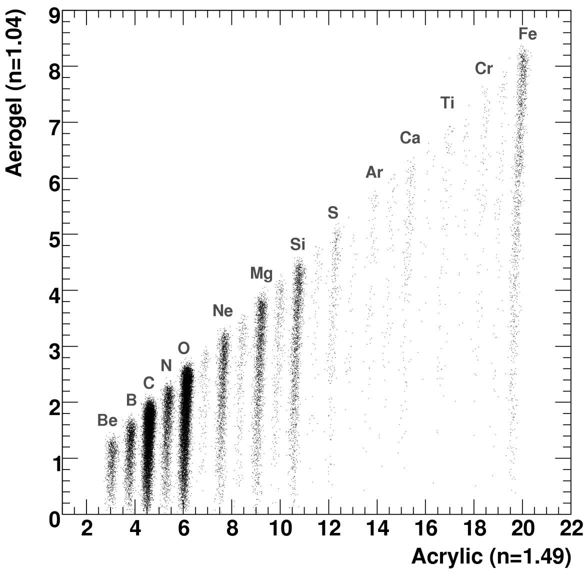

Fig. 4. Response of a combination of aerogel and acrylic Cherenkov counters to a simulated flux of cosmic-ray nuclei.

IV. CONCLUSION

It appears that the TRACER-PLUS concept satisfies all requirements concerning resolution in charge and energy for a measurement of the individual energy spectra of all primary and secondary cosmic-ray nuclei from Be to Ni. The detector system also has a very large geometric factor G: for TRACER we have G = 5 m^2 sr, and for a completely redesigned detector system, an increase by perhaps 50% seems not out of the question. Two or three long-duration balloon flights would then yield the desired total exposure of 500 m^2 sr days or more.

We do have to be concerned with a source of possible systematic error, namely the correction for secondary particles in the residual atmosphere. However, it appears that this problem can have an elegant solution: As the balloon will undergo day/night variations of typically 1-2 g/cm^2 in float altitude, one can measure the atmospheric production rate, using the plentiful particles at lower energy and assuming that the production cross sections do not change with energy. We currently study this process in simulations.

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