30TH INTERNATIONAL COSMIC RAY CONFERENCE

ICRC'07
Mérida, México

ICRC 2007 Proceedings - Pre-Conference Edition

# The TRACER Project: Instrument Concept, Balloon Flights, and Analysis Procedures

D. MÜLLER, M. AVE, P.J. BOYLE, F. GAHBAUER, C. HÖPPNER, J. HÖRANDEL[a], M. ICHIMURA[b], D. MÜLLER AND A. ROMERO-WOLF
*The University of Chicago, 5640 South Ellis Avenue, Chicago, IL 60637, USA*
*(a) University of Karlsruhe, Germany (b) Hirosaki University, Japan*
*dmuller@uchicago.edu*

**Abstract:** Accurate measurements of the composition and energy spectra of cosmic rays beyond the TeV energy region have been an experimental challenge for years. TRACER ("Transition Radiation Array for Cosmic Energetic Radiation"), is currently the largest cosmic-ray detector for direct measurements, and has been developed for long-duration balloon flights. The instrument is unconventional in that it uses only electromagnetic processes, such as measurements of ionization energy loss, Cherenkov light, and transition radiation, to make precision measurements that span more than four decades in energy, from 1 GeV/nucleon to energies beyond 10 TeV/nucleon. In its first long-duration balloon flight from Antarctica in December 2003, TRACER measured the energy spectra of the primary galactic cosmic-ray nuclei from oxygen (Z = 8) to iron (Z = 26). For a second LDB flight from Sweden in July 2006, the instrument was modified and upgraded in order to include the important light nuclei from boron (Z = 5) to nitrogen (Z = 7). We discuss the performance of TRACER in these two flights, review the response of the individual detector components, and the techniques employed in the data analysis.

## Introduction

The TRACER instrument ("Transition Radiation Array for Cosmic Energetic Radiation") has been developed to provide direct measurements of the elemental composition and energy spectra of cosmic-ray nuclei. The measurements should reach energies approaching the cosmic-ray "knee", hence the instrument exhibits the largest geometric factor ($\sim$ 5m$^2$ster) thus far realized in balloon-borne observations. TRACER has had three balloon flights: a test flight in New Mexico [1], and two long-duration balloon flights, in Antarctica [2] and in the Northern Hemisphere, respectively. In this paper, we shall summarize the overall program, including the key design and performance characteristics of the detector system.

## Instrument Description

In order to minimize the mass-to-area ratio of the instrument, TRACER uses purely electromagnetic techniques to determine charge Z and energy E (or the Lorentz-factor $\gamma$ = E/mc$^2$) of cosmic-ray nuclei; a nuclear interaction in the detector is not needed, and in fact, not desired. Thus, TRACER employs a combination of Cherenkov counters, plastic scintillators, gaseous detectors for specific ionization, and transition radiation detectors. The particles encountered in high-latitude flights may have a wide range of energies, from sub-relativistic energies ($<$ 1GeV/nucleon) up to the rare high-energy particles of interest here, with energies higher by four orders of magnitude.

The discrimination of the rare high-energy particles from the much more abundant (by about four orders of magnitude) low-energy flux represents a particular challenge for TRACER. This discrimination is achieved with an acrylic Cherenkov counter, combined with ionization measurements with plastic scintillators and gas proportional tubes ("dE/dx counter"). For sub-relativistic particles above the Cherenkov threshold, the Cherenkov signal increases with energy and reaches saturation around $\gamma$ $\sim$ 10, while the ionization signal de-

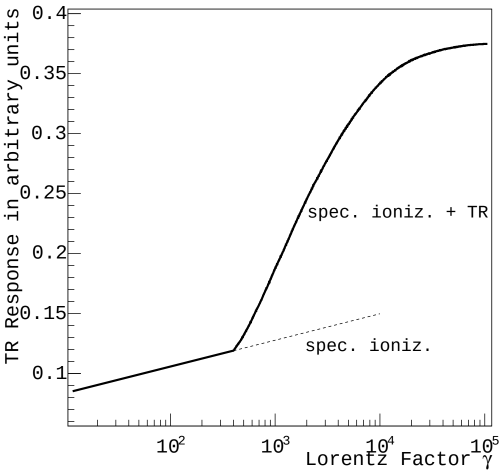

Figure 1: Energy response of the Transition Radiation Detector

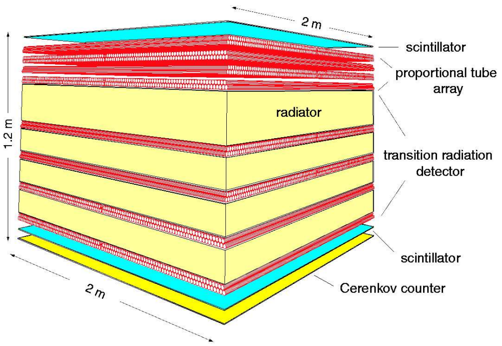

Figure 2: Schematic drawing of TRACER

creases according to the Bethe-Bloch formula and reaches minimum ionization around $\gamma$ = 3.9. The signal remains at that level for the plastic scintillator, but increases again slowly with energy for the gaseous detectors (the "relativistic rise"). The signals of the Cherenkov counter do not only identify sub-relativistic particles, but also measure their energies.

The very highest particle energies ($\gamma > 500$) are identified with a transition radiation detector (TRD), which again, employs gas proportional tubes. The response of the TRD is shown in Figure 1. Up to the TR threshold ($\gamma \approx 400$), its response is identical to the that of the gaseous dE/dx counter, but at higher energies, the superimposed TR x-rays lead to a combined signal that rises steeply with energy. These detector elements are combined in TRACER as shown in figure 2. The instrument contains two plastic scintillators (2 m x 2 m, 0.5 cm thick) on the top and bottom and one acrylic Cherenkov counter (2 m x 2 m, 1.3 cm thick) at the bottom. For the 2006 balloon flight, a second, identical Cherenkov counter was added on top of the detector. Sandwiched between the top and bottom counters are 1584 single-wire proportional tubes (2 cm diameter, 2 m length) which are arranged in layers in two orthogonal directions as shown: half of the tubes at the top measure the ionization energy loss, while the other half is interspersed below plastic-fiber radiators to form a TRD.

## Balloon Flights

A one-day test flight of TRACER was performed from Fort Sumner, NM, in 1999, and the results have been published in Gahbauer et al. [1]. A long-duration flight from McMurdo, Antarctica, was launched in December 2003, and yielded data with zero dead time for ten days. The analysis of these data is now complete, and results will be presented here and in two related papers in these proceedings (Boyle et al. [3] and Ave et al. [4]). For these flights, the readout electronics was limited in dynamic range; hence, the elements covered ranged from oxygen (Z = 8) to iron (Z = 26). After the 2003 flight, the electronics were upgraded to permit inclusion of the important light secondary nuclei in the measurement. Hence, the elements from boron (Z = 5) to iron (Z = 26) are now covered. In order to improve the charge resolution, a second acrylic Cherenkov counter was installed. TRACER was then launched for a second long-duration flight from Kiruna, Sweden, in July 2006. Unfortunately, this flight had to be terminated after 4.5 days afloat, due to lack of an agreement which would have permitted continuation of the flight over northern Russia.

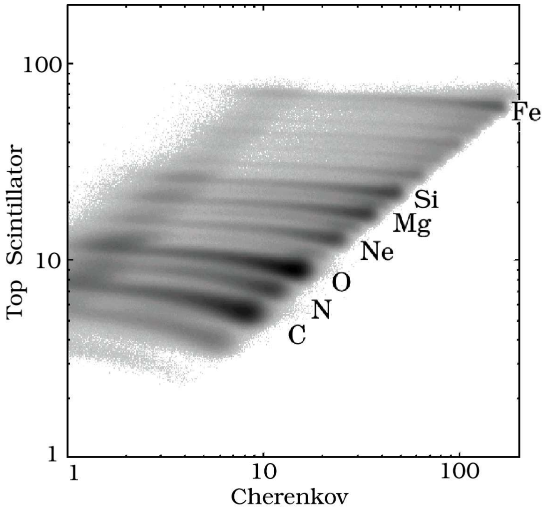

Figure 3: Scatter plot of top scintillator vs. Cherenkov signal in arbitrary units.

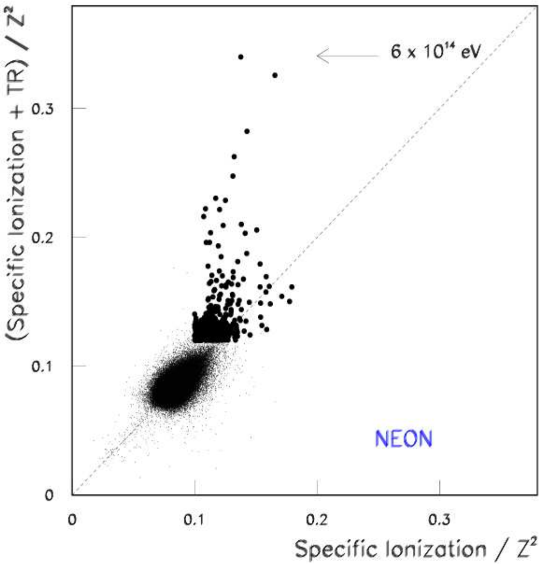

Figure 4: Scatter plot of TR vs. dE/dx signal for neon nuclei. The units are arbitrary.

## Data Analysis

We now shall briefly summarize the analysis procedures used for the 2003 flight. The analysis proceeds in the following steps: First the trajectory of each particle through the instrument is reconstructed, using the signals measured in the proportional and TRD tubes. Utilizing the fact that the signals are proportional to the pathlength through the tubes (within statistical fluctuations), one obtains a positional accuracy of 2-3 mm, which is much smaller than the tube radius. Subsequently, the signals of scintillators and Cherenkov counters are corrected for spatial non-uniformities in response according to response maps determined with muons before the flight, and verified by the flight data themselves.

Individual elements are cleanly identified from cross-correlations of scintillator and Cherenkov signals as shown in Figure 3. Cross-correlations between Cherenkov signals and ionization signals nuclei provide the means to separate low-and high-energy particles (i.e., below or above minimum ionization), see Höppner [5] and Romero-Wolf [2]. The magnitude of the Cherenkov signals determines the low-energy spectrum, from about 0.5 to 5 GeV/nucleon. The important and rare high-energy particles are cleanly identified in a cross-correlation of the signals of the ionization tubes (“dE/dx counters”) with those measured with the TRD tubes. This is shown in Figure 4 for neon nuclei. Note that, for this figure, low energy particles (below minimum ionization) are removed. As expected, the majority of events lead to identical signals in dE/dx and TRD tubes; they have energies between a few GeV/nucleon and about 400 GeV/nucleon. At higher energies, the appearance of transition radiation enhances the TRD signals. This enhancement is the means to assign energies in the 500 GeV/nucleon to 10,000 GeV/nucleon region to these particles. Note how cleanly these rare high-energy particles can be identified : there are no background counts whatsoever in the “off-regions” of the scatter plot !

In order to determine the differential energy spectra on top of the atmosphere from these measurements, the selection efficiencies of the data analysis need to be known. As Table 1 shows, these are, in general, quite high. As an example for the results, Figure 5 shows the differential energy spectrum for neon nuclei. Note that the spectrum shown represents absolute intensities; there is no arbitrary normalization.

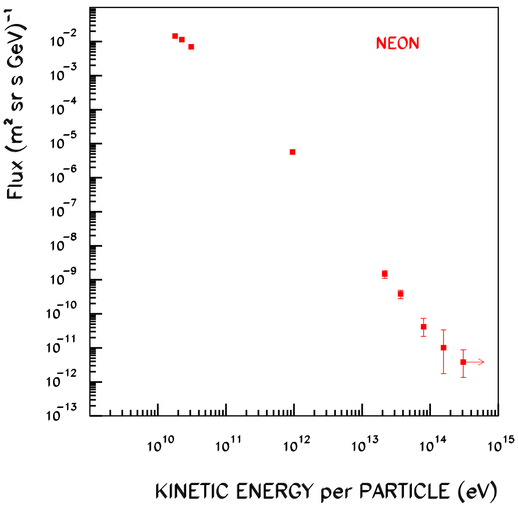

Figure 5: Differential energy spectrum for the single element neon from TRACER 2003.

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

| | **Oxygen** | **Iron** |
|---|---|---|
| Interaction - Atmosphere | 82% | 72% |
| Interaction - Instrument | 65% | 48% |
| Tracking Efficiency | 95% | 95% |
| Top Charge Efficiency | 89% | 90% |
| Bot Charge Efficiency | 100% | 100% |

## Conclusion

The 2003 flight of TRACER has determined the energy spectra of the major primary nuclei for oxygen (Z = 8) to iron (Z = 26). These results, and their interpretation, will be shown in the accompanying papers of Boyle [3] and Ave [4]. The analysis of the 2006 flight data, which also include measurements of the lighter cosmic-ray nuclei, down to boron (Z = 5), is currently in progress.

While the TRACER results extend our knowledge of the cosmic ray composition well into the $10^{14}$ eV per particle energy region, this upper limit is purely due to counting statistics; the detector response would permit measurements to considerably higher energies if larger exposures become available.

## Acknowledgments

This work has been supported by NASA grants NAG5-5305, NN04WC08G and NNG06WC05G. MI acknowledges the Grant-in-Aid for Scientific Research of the Japan Society for the Promotion of Science(JSPS), No. 17540226. Numerous students have participated in this research under support from the Illinois Space Grant Consortium. We gratefully acknowledge the services of the University of Chicago Engineering Center and the Columbia Scientific Balloon Facility.

## References

[1] F. Gahbauer et al. *ApJ*, 607:333, 2004.
[2] A. Romero-Wolf et al. *Proc. 29th ICRC*, 3:97, 2005.
[3] P. J. Boyle et al. *Proc. 30th ICRC*, 2007.
[4] M. Ave et al. *Proc. 30th ICRC*, 2007.
[5] C. Höppner et al. *Proc. 29th ICRC*, 3:73, 2005.