The TRACER instrument: A balloon-borne cosmic-ray detector


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ABSTRACT

We describe a large-area detector for measurements of the intensity of cosmic-ray nuclei in balloon-borne exposures. In order to observe individual nuclei at very high energies, the instrument employs transition radiation detectors (TRD) whose energy response extends well beyond 10^6 GeV amu^-1. The TR measurement is performed with arrays of single-wire proportional tubes interleaved with plastic-fiber radiators. An additional energy determination comes from the specific ionization in gas and its relativistic rise which is also measured with proportional tubes. The tubes also determine the trajectory of each cosmic-ray nucleus with mm-resolution. In total, nearly 1600 tubes are used. The instrument is triggered by large-area plastic scintillators. The scintillators, together with acrylic Cherenkov counters, also determine the nuclear charge Z of each cosmic-ray particle, measure the energy in the GeV amu^-1 region, and discriminate against low-energy background. We describe the details of this detector system, and discuss its performance in three high-altitude balloon flights, including two long-duration flights in 2003 and 2006 at Antarctic and Arctic latitudes, respectively. Scientific results from these flights are summarized, and possible future developments are reviewed.

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1. Introduction

Direct observations of cosmic rays must be performed above the atmosphere, either on spacecraft or high-altitude balloon. The particle intensities decrease rapidly with increasing energy. Hence, large area detectors are required for measurements at high energies. If instruments of several square meters in area are available, and exposed for hundreds of days, the measurements may approach the energy region around 10^15 eV particle^-1. It is often suspected that in this energy region, the cosmic-ray composition changes as the Galactic accelerator approaches a rigidity-dependent cutoff [1]. Clear evidence from direct observations for such a change does not yet exist. At still higher energies, direct measurements that can identify the primary cosmic-ray particle are not possible with currently available instrumentation, and one must resort to indirect observations of air showers in the earth’s atmosphere [2,3].

We will describe here an instrument that has been developed for long-duration balloon flights with the goal of measuring the details of the elemental composition and energy spectra of cosmic-ray nuclei at as high an energy as possible. The mass of a balloon payload is limited to at most a few tons. Within this constraint, measurement techniques that rely on electromagnetic interactions can maximize the detector area more efficiently than techniques utilizing nuclear calorimetry. For the instrument discussed here, transition radiation detectors (TRD) are used, and are augmented with Cherenkov counters and with detectors that measure specific ionization in gas.

Transition radiation detectors (TRD) are sensitive to particles with very high Lorentz factors γ. TRD’s are often used in particle physics or cosmic-ray experiments as threshold devices to discriminate between light and heavy particles of known momentum, for instance between electrons, pions, and protons. An accurate determination of the energy of a particle from a measurement of the transition radiation (TR) intensity is much more difficult for singly charged particles because of the large signal fluctuations. The situation becomes qualitatively different if one deals with highly charged particles such as cosmic-ray nuclei: the relative magnitude of fluctuations decreases with Z (where Z is the charge number), and rather precise measurements of the energy (or Lorentz factor) can be made.

Key features of TRD’s include: (a) a favorable area-to-weight ratio, (b) the possibility of accelerator calibrations with beams of...
electronics or pions at large Lorentz factors, for which beams of nuclei are not available, (c) the fact that the TR-signal scales strictly with $Z^2$. Therefore, relative signal fluctuations decrease as $1/Z$, (d) a good match between the TR-detector factor range of a TRD (10$^{5}$–10$^{6}$) and the range of energies that can be reached in direct cosmic-ray measurements with reasonable exposure factors, (e) the possibility of multiple redundant measurements in a layered radiator/detector configuration, and (f) good energy resolution, typically of the order of 10% or better for the heavier nuclei at $\gamma \approx 1000$.

The use of a TRD for precise cosmic-ray energy measurements was first demonstrated by the cosmic-ray group at the University of Chicago with a large detector called CRN (“Cosmic-Ray Nuclei instrument”). Like most TR detector systems, CRN employed a sandwich configuration of several radiators and multi-wire proportional chambers (MWPCs), each radiator being followed by an MWPC. The MWPCs had thin, planar windows and operated at atmospheric pressure. Necessarily then, the detectors had to be enclosed in a pressurized container. CRN was flown on the space shuttle in 1985 [4]. However, further development and additional flights of CRN were terminated after the Challenger accident in 1986. Around the same time as Challenger, long duration balloon flights (LDB) around the northern and southern poles became available. LDB offered the possibility of flights of several weeks duration at moderate cost. Therefore, a new balloon payload, TRACER (Transition Radiation Array for Cosmic Energetic Radiation), utilizing the heritage of CRN, was developed for measurements in an unexplored region of the cosmic-ray spectrum. To minimize the weight it was advantageous to design the instrument such that it could be exposed to ambient pressure, without requiring a pressurized gondola. This led to the replacement the MWPCs of CRN with arrays of single-wire proportional tubes of that could withstand external vacuum.

In this paper, we explain the measurement principles, describe the TRACER detector, and discuss its performance during the three flights thus far. The scientific results are published elsewhere [5–8].

2. Instrument description and performance

2.1. Overall description and balloon flights

TRACER is designed to measure the energy spectra of the heavier cosmic-ray nuclei from boron ($Z=5$) to iron ($Z=26$). In order to reach energies in the 10$^{14}$–10$^{15}$ eV particle$^{-1}$ region in repeated long-duration balloon flights, the detector has a geometric factor of $\approx 5 \text{ m}^2 \text{ sr}$ and is currently the largest balloon-borne cosmic-ray detector in existence. The instrument is shown schematically in Fig. 1.

TRACER must perform two measurements for each incident cosmic-ray nucleus: (1) identify its nuclear charge $Z$. Isotopic resolution is not attempted, and, in fact, is beyond current measurement techniques at these energies. (2) measure its energy $E$ or Lorentz factor $\gamma$.

Cosmic-ray nuclei at these energies are fully ionized. Therefore, their nuclear charge is determined with two identical pairs of scintillation and acrylic Cherenkov counters placed at the top and bottom of the instrument. The scintillation counters also provide the instrument with a coincidence trigger. The charge measurement utilizes the fact that both the ionization energy loss generating the scintillator signal, and the Cherenkov light yield, scale with $Z^2$. However, the energy dependence in both counters is characteristically different. Consistency in the charges measured on top and bottom, respectively, ensures that nuclei have not undergone a charge-changing nuclear interaction within the detector.

Layers of gas-filled single-wire proportional tubes (a total of 1584, each 2 m in length) between the top and bottom counters measure the specific ionization $<dE/dx>$, or form a transition radiation detector (TRD) which measure $<dE/dx+TR>$. Both, the $dE/dx$ and TR signals scale with $Z^2$.

TRACER determines the energy of individual cosmic-ray nuclei in three regions: (a) at low energies, up to a few GeV amu$^{-1}$, from the signals of the Cherenkov counters, (b) from about 10–400 GeV amu$^{-1}$ from the relativistic increase of the ionization signal measured in the proportional tubes, and (c) above 400 GeV amu$^{-1}$, from the signals of the TRD (see Fig. 2). The TRD is expected to saturate at energies around 30,000 GeV amu$^{-1}$. Because of the steeply falling energy spectrum, TRACER cannot cover energies beyond this region.

As mentioned, statistical fluctuations in the $dE/dx$ and TR signals preclude energy measurements for low-$Z$ particles, such as protons and helium nuclei with this instrument.

The instrument includes various analog and digital electronic circuits to read out the detector subsystems, format and store the data onboard, receive commands and transmit data to the ground. To save weight, the entire detector, apart from a small number of pressure sensitive electronic devices, operates at ambient pressure during the balloon flights. This creates a number of technical challenges, including the danger of corona discharge at the detector elements under high voltage, and local overheating of the electronics. The proportional tubes have an on-board gas supply and regulation system that allows for regulation of the gas pressure in flight. Electric power during the LDB flights comes from onboard photovoltaic solar arrays. Passive thermal protection for TRACER is provided through the use of foam insulation and Mylar sun shields. Fig. 3 shows the TRACER instrument ready for launch in Antarctica in 2003.

TRACER has had three successful flights on high altitude balloon thus far. For each flight a 39 million cubic-foot balloon was used. Typical float altitudes were 36–40 km, corresponding to a residual atmosphere of 3.5–6 g cm$^{-2}$. The instrument and data

Fig. 1. Schematic diagram of the TRACER instrument.

Fig. 2. Energy response of TRACER [6]. Three measurements are combined to cover more than four decades in energy. All signals scale with $Z^2$. 
have been recovered intact after each flight. A summary of flights is given below and also in Table 1 in Section 3:

Test flight (T99): Launch from Ft. Sumner, USA on September 20, 1999. The flight was 28 h in duration and served as a test flight for the subsequent longer duration flights.

Long Duration Flight I (LDB1): Launch from Antarctica on December 12, 2003. The circumpolar flight lasted 14 days, and a total of $5 \times 10^7$ cosmic-ray particles (with 4 kbit/event on average) were collected. TRACER was the first payload deployed using the newly developed Antarctic launch vehicle, and also was, at the time, the heaviest cosmic-ray payload launched in Antarctica (for flight trajectory see Fig. 4).

For the first two flights, the trigger threshold was set such that the instrument had full efficiency for the elements oxygen to iron.

Long duration flight II (LDB2): Launch from Kiruna, Sweden on July 8, 2006. The flight was intended to be circumpolar, but, had to be terminated after 4.5 days due to the lack of permission to fly over Russian territory. Improvements to the instrument allowed the inclusion of the lighter elements boron, carbon, and nitrogen in the measurement. A total of $3 \times 10^7$ cosmic-ray particles (with 8 kbit/event on average) were collected.

The scientific results of T99 and LDB1 have been published [5,6]. Preliminary results for LDB2 have been presented [9,10] and the complete data analysis is being submitted for publication [8].

3. Details of the detector subsystems

3.1. Scintillators and Cherenkov counter

The geometric factor of TRACER is defined by large scintillator and Cherenkov counters of $2 \times 2$ m$^2$ active area. In order to achieve a relatively uniform response with a reasonable number of photomultiplier tubes (PMT’s), the scintillator and the Cherenkov counters are divided into four quadrants and are read out via
wavelength shifter bars. The arrangement is shown schematically in Fig. 5. PMT’s of relatively small size, commensurate with the counter thickness, are used. Details of the materials are summarized in Table 2.

The scintillator system detects \( \sim 40 \) photoelectrons for a singly charged particle at minimum ionization energy, whereas the Cherenkov system detects \( \sim 2–3 \) photoelectrons for a singly charged particle in Cherenkov saturation. These numbers represent the sum over all PMT’s that participate in the measurement.

For each scintillator PMT, signals from both the anode and from the last dynode are used. The anode signals, via a summing amplifier and a discriminator, serve as the coincidence trigger. The dynode signals are charge-integrated and analyzed individually. The Cherenkov counter is not used in the trigger, and only the dynode signals are analyzed. Note that the Cherenkov counter on top of the instrument was not installed for the first two flights of TRACER.

3.2. Proportional tube array

The proportional tube array must track the particle through the detector as well as measure its energy. The array consists of eight double layers of cylindrical single-wire tubes in closest packing. Each tube is 2 cm in diameter and 200 cm long. The design of the proportional tubes must satisfy a number of requirements: the tube must (a) hold an anode wire at an appropriate tension precisely at the center, (b) contain the detector gas without leaking, (c) allow for gas purging, high-voltage, and signal feed-throughs, (d) have walls that are transparent to X-rays, and (e) require a manageable amount of labor and tedium to construct. A detailed description of the design is given in Appendix A. Table 3 summarizes the major parameters for the proportional tubes.

The proportional tubes are hermetically connected on one end to manifolds (see Fig. 6). Each manifold serves 99 closely packed tubes, and a total of sixteen manifolds is required for the instrument. The anode wire is fed into the manifold and each individual channel is read out via internal coupling capacitors. This arrangement removes the need for corona-proof high-voltage feed-throughs for each individual tube. To allow for thermal expansion of the proportional tubes, the opposite ends of the tubes are connected to smaller gas manifolds via flexible hoses. For each manifold the tube array is supported by a tightly stretched horizontal mylar membrane. To allow for the reconstruction of the trajectory of the particle, the manifolds are oriented in alternate x- and y-directions. Each particle traversing the entire detector will encounter a total of 16 individual tubes. Gain variations along the tubes, for instance due to a slight drooping of the anode wire, are less than 5% if the tubes are supported by a flat surface.

3.2.1. The \( dE/dx \) array

The four double layers of tubes at top of the proportional tube array measure the specific ionization in gas \( (dE/dx) \) for each cosmic-ray nucleus traversing the array. The response versus energy (or Lorentz factor \( \gamma \) ) is shown in Fig. 2. One notices that \( dE/dx \) is dropping rapidly at low energies according to the Bethe–Bloch relation [11], reaches a minimum at \( \gamma \approx 3 \), and then exhibits a logarithmic increase up to Lorentz factors of several hundred, or energies of several hundred GeV nucleon\(^{-1}\). If the signal

<table>
<thead>
<tr>
<th>Table 2</th>
<th>Components used in the scintillator and Cherenkov counters.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Component</td>
<td>Type</td>
</tr>
<tr>
<td>Scintillator</td>
<td>BICRON 408</td>
</tr>
<tr>
<td>Cherenkov</td>
<td>Polycast Acrylic</td>
</tr>
<tr>
<td>Waveshifter bars</td>
<td>BC 482A</td>
</tr>
<tr>
<td>PMT</td>
<td>Photonis XP1910</td>
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<table>
<thead>
<tr>
<th>Table 3</th>
<th>Summary of major parameters of the proportional tubes.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tube dimension</td>
<td>Length 200 cm; diameter 2 cm</td>
</tr>
<tr>
<td>Wall material</td>
<td>Mylar; 3 layer, thickness 76 ( \mu m )</td>
</tr>
<tr>
<td>Cathode</td>
<td>Aluminization on inner Mylar layer</td>
</tr>
<tr>
<td>Anode wire</td>
<td>Stainless steel; diameter 50 ( \mu m )</td>
</tr>
<tr>
<td>Gas mixture</td>
<td>Xe:CH(_4) (50:50) (T99 and LDB1)</td>
</tr>
<tr>
<td>Gas pressure</td>
<td>0.5 atm (T99 and LDB1)</td>
</tr>
<tr>
<td>High voltage</td>
<td>1000 V (T99 and LDB1)</td>
</tr>
</tbody>
</table>

Fig. 6. Schematic of gas manifold for proportional tubes. Figure is not drawn to scale and only 3 of the 99 tubes are shown.
fluctuations are sufficiently small, this increase can be utilized for energy measurements.

3.2.2. Transition radiation detector
The TRD is comprised of four double layers of proportional tubes situated below the dE/dx array, with plastic fiber radiators located directly above each double layer. The tubes measure the superposition of ionization energy loss (dE/dx) and signal due to TR X-rays generated in the radiators for highly relativistic particles. The radiators consist of blankets of “thick” and “thin” fibers that are identical to those used on CRN [44] and Table 4). The specific design of these radiators was determined in a detailed optimization study using accelerator exposures of different configurations [12]. For additional comments on the TRD calibration, see also Section 4.1. The top radiator, with a thickness of 17.8 cm, is somewhat thicker than the following three radiators (each 11.25 cm thick) in order to compensate for the lack of “feed-through” X-rays in the first tube layer that may be generated but detected only after passing through more than one radiator/detector pair. This arrangement has proved to be useful for obtaining a uniform energy response of all detector layers in accelerator calibrations [4].

The response of the TRD is shown in Fig. 2. One notices the sharp increase in signal above the onset of TR at high γ-values, which permits accurate energy measurements in this region. Due to the steeply falling nature of the energy spectrum of cosmic rays, most events are at energies below the TR threshold. For these events, the tubes of the dE/dx array and the tubes of the TRD will measure the same signal, within statistical fluctuations.

3.3. Electronics and data acquisition

3.3.1. Front-end electronics
The front-end electronics systems provides the coincidence trigger for the instrument, and also processes all signals from the PMT’s, the proportional tubes and from various housekeeping sensors (such as count rates, temperatures, gas pressures etc.). After digitization, the data are formatted into events that can be stored on-board and/or transmitted to the ground by telemetry.

Fig. 7 shows a simple schematic overview of the electronics. The last dynode signals of all the PMT’s are integrated with custom-built charge sensitive amplifiers (CSA’s), and analyzed with 12-bit accuracy by custom-built peak-detecting ADC’s. The signal from each PMT is recorded for every event.

Charge pulses from the nearly 1600 anode wires of the proportional tubes are integrated through AMPLEX VLSI chips [13], held via track and hold circuitry, and multiplexed into 10-bit ADC’s. The proportional tube system requires careful tuning: First, the charge delivered from the wire should not exceed the pico-Coulomb range in order to avoid deviations from linear response due to space charge effects. In practice, this means that the high voltage for the proportional tubes be adjusted to insure a gas amplification which is very low, less than ten. Second, the system must accommodate a dynamic range of nearly 10^6: the signals vary with Z^2 of the particle (i.e. Z^2=25 and 676 for boron and iron, respectively) and for each Z, may vary by an additional factor of at least 10 due to varying pathlengths of the particle through the tubes, and due to the appearance of transition radiation. However, the AMPLEX chip, with a maximum output signal of 1.2 V, accommodates only a dynamic range above noise of a few hundred. Hence, the signal for each tube is split resistively in the ratio of 1:14 into two separate AMPLEX channels, as shown in Fig. 8. This configuration was developed by Swordy [14] for the CREAM instrument [15]. Proper setting of the hold time depends on the drift times of electrons in the tubes. Fig. 9 shows the time response for two gases operating at various high voltages. The hold-time can be adjusted during flight via commands from the ground station.

To minimize the size of each event, a zero-suppression system is utilized for the proportional tubes, and only signals which are above the pedestal threshold are stored. The pedestal levels and their variations are monitored periodically throughout the flight,
and the threshold levels can be adjusted individually for each tube by telemetry command. Note that for T99 and LDB1, only one AMPLEX channel was connected to each wire. Hence, the dynamic range of the signals was reduced, and only the detection of nuclei from oxygen (Z=8) to iron (Z=26) was possible with sufficient accuracy.

3.3.3. Telemetry

When line-of-sight (LOS) contact exists between the balloon payload and the ground station, the data stream generated by TRACER can be fully transmitted via telemetry at a bandwidth of 0.5 or 1.0 Mb s⁻¹ for the two LDB flights, respectively. Data also includes various instrument parameters such as gas pressures, temperatures of critical components, high voltage levels, counting rates, and the status of the hard disks. For most of the duration of the flight however, data transmission is available only with limited bandwidth of 6 kb s⁻¹ via the NASA TDRSS system [16]. This is shown schematically in Fig. 10. While the data transmitted by TDRSS amounts to only 1–2% of the total data rate, this information is vital for real-time diagnostics of the instrument.

3.3.4. Commanding

During the flight, it is necessary to execute commands from ground to operate the instrument and to respond to unforeseen situations. For example, one may activate solenoid valves in the gas system, turn on and adjust high voltage for the PMT’s and proportional tubes, select trigger thresholds, or map the pedestal levels of the AMPLEX amplifiers. Commands are transmitted via the TDRSS system, with an IRIDIUM Satellite link available as backup. Most of the commands are passed by a command receiver to the onboard CPU, which interprets and executes them. However, to minimize the chance that an onboard CPU malfunction could jeopardize the mission, critical commands, such as turning the instrument power on and off, rebooting the CPU, and resetting the electronics system, are executed directly without involvement of the onboard CPU.

3.3.5. Power system

The power consumption for TRACER is ≈250 W. For long-duration flights, solar panels are required in conjunction with a power control unit (PCU), a buffering battery pack, and a rotator against the balloon to keep the panels in a sun-facing orientation. The solar panels are mounted on the side of the instrument as shown in Fig. 3. The PCU, designed by MEER instruments, connects or disconnects successive solar panels to balance the need for power and recharging of the batteries. A low-weight rechargeable Lithium-ion battery pack (Lithium Technologies Inc.) was used in LDB1. Towards the end of the first orbit of the balloon around the South Pole, a catastrophic failure of the batteries occurred, limiting the operation of the instrument to 10 days. Therefore, for LDB2 nickel metal hydride batteries (Cobasys Inc.) were used, and no problem was encountered.

3.4. Mechanical systems

3.4.1. Mechanical structure

The TRACER instrument is housed in a 2 × 2 × 3 m³ open support structure as shown in Fig. 11. The structure is designed to be strong enough to support the weight of the payload and to withstand substantial shocks during termination and landing (5g horizontal, 7g diagonal, and 10g vertical). The instrument is divided into two levels. The upper level contains the science detectors, while the lower level contains batteries, gas supply and distribution system, and the flight control and telemetry systems.¹⁰ Systems that are sensitive to low pressure such as the CPU, high-voltage converters, and data disks are housed within a pressurized vessel. The rest of the instrument is exposed to a low pressure environment (3–6 torr) during flight.

Before each Long Duration Flight, the entire instrument was tested under vacuum at the B2 testing chamber of the NASA Glenn Research Center, Plum brook, Sandusky, Ohio. This ensured that the proportional tubes and gas system (see Section 3.4.2) are gas tight, the high voltage connections are properly encapsulated and free of corona discharge, and that the front end electronics do not overheat.

3.4.2. Gas system

The proportional tube system of TRACER has a total volume of 1000 l which is segmented into 16 manifolds, each of ≈60 l as shown schematically in Fig. 12. Each manifold is connected to 99

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¹⁰ The flight control and telemetry systems are supplied by the Columbia Scientific Balloon Facility, Palestine, Texas, USA.
tubes and is serviced by individual valves on the input and output. On the ground the entire system is operated with an Ar:CH₄ mixture. Just before launch, the system is purged with a Xe:CH₄ gas mixture.

For T99 and LDB1, the Xe:CH₄ gas mixture was 50%:50% by volume at 0.5 atm. To further reduce intrinsic signal fluctuations, and hence improve the energy resolution, the xenon content was increased for LDB2 by a factor of 4 (95%:5% at 1 atm). This is important for the measurement of the light elements (B, C, and N).

TRACER carries an additional 3000 l of Xe:CH₄ on-board to allow repeated gas-purges of the proportional tubes. For the duration of each flight there was no indication of a deterioration of the performance of the proportional tubes due to gas poisoning (see Fig. 13) and no gas-purges had to be performed. This is contrary to the behavior on the ground where a noticeable loss of gain and resolution occurs after ~2 days, presumably due to diffusion of oxygen or water vapor into the proportional tubes. This result is of great practical importance if flights of such devices for much longer duration (for instance in space) are anticipated: there seems to be no need for gas-purging at the time scales of at least a few weeks except for the provision of make-up gas to correct for minor leaks.

3.4.3. Thermal protection

The TRACER instrument must operate reliably in a hostile thermal environment. One side of the instrument is exposed to 1400 W m⁻² radiation from the sun, while the opposite side is exposed to space. The bottom of the instrument may receive a fraction of the sun’s radiation due to reflection from the earth’s surface or clouds. Depending on conditions this fraction is quite variable (20–95%). Furthermore, electronics operating at balloon pressures cannot rely on thermal convection for cooling, and thus are potentially vulnerable to local overheating.

These challenges are addressed with an almost completely passive thermal protection system that has been used in all three flights, albeit with slight modifications for each environment. A more detailed description of the computer modeling and actual design of the thermal system is given in Appendix B.

Several temperature sensors were attached to various components of the instrument (electronics, detectors, etc.) during all three flights. Temperatures between ±5 and ±25 °C have been measured, with only a few degrees gradient across the instrument, and are consistent with temperatures predicted by the thermal model. Fig. 14 shows an average temperature profile for the instrument during LDB1.

4. Detector performance

4.1. Simulations and calibrations

The response of the detectors in TRACER is determined from laboratory tests, accelerator calibrations, and Monte Carlo simulations. The Monte Carlo simulation is based on the CERN GEANT4 package [17]. The Gh4Ionization package is used to simulate the passage of heavy nuclei. The simulation models the response for
the proportional tube array, scintillators, and Cherenkov counters, including the effects of $\delta$-rays.

To understand the calibration of the TRD, one needs to realize that the detectable TR signals, and their magnitude relative to the ionization signals of the primary particles, depend on the structure and composition of the radiator, and on the gas composition and thickness of the detector. For periodic radiators, the signal can be predicted by analytical expressions which are in good agreement with measurements [18–20]. However, radiators made of fibers or foams are required for practical reasons [21], and composite radiators utilizing layers of materials with different properties have been developed to obtain TR signals over an extended energy range [12,22]. Simulation codes for the response of such radiators exist within GEANT4. However, an accurate calibration requires verification with accelerator beams. As TR detectors measure the Lorentz factor $\gamma$, in contrast to ionization calorimeters which attempt to measure the total energy deposited by interacting nuclei, an accelerator calibration of TRD’s is possible with beams of singly charged low-mass particles (electrons and pions) that are available for the entire $\gamma$-range of interest. The possibility of such calibrations, however tedious they may be in practice, is a significant advantage over calorimeters, where the energy calibration includes extrapolations and simulations at high energies.

For T99 and LDB1 the configuration of the radiators was identical to that used in the CRN instrument [4], and the dimensions and gas content of the proportional tubes was deliberately chosen to be as close as possible to those of the MWPC system of CRN. This configuration had been developed [12] with the aim of defining a combination of radiators using several different fiber packages such that a measurable TR-signal is generated which increases with Lorentz factor gamma over a wide range, covering about two decades above a $\gamma$-value of a few hundred. The CRN instrument was calibrated at Fermilab with pions, muons, and electrons, and the energy response function is shown in Fig. 15. The average signal, shown as a function of Lorentz factor, represents the superposition of ionization loss and transition radiation. The contribution of transition radiation becomes noticeable at Lorentz factors $\gamma > 450$, and the signal rises steeply above this threshold. This same response function was adopted for TRACER (T99 and LDB1).

For the 2006 flight (LDB2), the xenon-content in the tubes was increased by nearly a factor of 4. This was necessary in order to reduce the statistical signal fluctuations (see below) to a level that permitted measurements of the light nuclei with $Z > 4$. The enhanced Xe content increases the conversion of TR X-rays, but also increases the ionization signal. Extrapolating from accelerator test measurements [12], the combination of these two effects moves the TR threshold to a higher value of about $\gamma = 785 \pm 140$, and reduces the relative magnitude of the TR signal by $\sim 19\% \pm 3\%$. The uncertainties reflect the fact that this configuration has not yet been verified by detailed accelerator measurements.

Below the TR threshold, the ionization signal exhibits a slow increase above the minimum-ionization level (the "relativistic increase"). The magnitude of the increase is determined by simulation and verified by the CR data themselves. The increase amounts to 40% and 33%, for the lighter and heavier gas mixtures, respectively, over the range from $\gamma = 10$ to $\gamma = 440$. Use of this rise for energy measurements is possible if the intrinsic signal fluctuations are smaller than the magnitude of the rise.

The signal fluctuations decrease essentially with $1/Z$ (where $Z$ is the charge number of the particle). Consequently, the energy resolution improves with increasing $Z$. Fig. 16 shows the energy resolution from the ionization signals measured with cosmic-ray particles at 100 GeV amu$^{-1}$ as a function of $Z$ (average signal from 16 layers of proportional tubes). The improvement in resolution achieved with the heavier gas mixture is quite significant. The energy resolution obtained at higher $\gamma$-values with the TRD is much better than that from the ionization measurement, due to the steep rise of the response curve. Again, the resolution improves with increasing $Z$. This is shown in Fig. 16 for the heavier gas mixture at 1500 GeV amu$^{-1}$. Fig. 16 also depicts the

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**Fig. 14.** Altitude, temperature and rate profiles for LDB1. The step in the trigger rate corresponds to a lowering of the high voltage on the scintillators.

**Fig. 15.** Energy response of the Transition Radiation Detector as measured at accelerators. Except for two highest-energy data points, these measurements have been published previously [4]. The open triangles refer to measurements of the specific ionization, without TR. The grey scale is logarithmic.

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11 A combination of the Cherenkov, ionization and TR signals allows for an accurate determination of the ionization signal corresponding to minimum ionization ($\gamma = 3.96$) and the onset of TR ($\gamma = 440$ and 785 for LDB1 and LDB2, respectively)
4.2. Effects due to $\delta$-rays

When a relativistic nucleus traverses the instrument, knock-on electrons, or $\delta$-rays, are produced and contribute to the measured signals in all detectors, the gas proportional tubes as well as the Cherenkov and scintillation counters.

Contribution to the signals in the proportional tubes come from the ionization loss of the primary particle and from $\delta$-rays that may be generated in the tube walls. A particle passing through near the edge of the tube will encounter more wall material than a particle passing near the center (see Fig. 17). Consequently, the number of $\delta$-rays produced is increased and some of the low-energy $\delta$-rays, which are emitted at large angles, can escape more easily into the proportional tube. Therefore, the $\delta$-ray contribution to the signals is significantly larger than for particles passing through the center of the tube. The effect has been studied in detail [23] and it has been shown to become negligible if the pathlength of the particle through the gas is greater than a few mm.

Another effect of potential concern is the contribution of signals in the tubes from high energy $\delta$-rays produced in more distant regions of the instrument, for instance in the radiator material of the TRD.

Fig. 18 shows an output of the simulation for three simulated iron nuclei. Each point represents an energy deposit in the proportional tubes and illustrates the sizable halo of $\delta$-rays generated by each nucleus. As the number of $\delta$-rays increases with growing depth in the instrument, the possibility of a related increase of the tube signal has been investigated. A systematic study, in which TRACER is exposed to a simulated flux of many thousands of particles, has shown that this behavior does not occur. The average signal, normalized to the pathlength, in the proportional tubes for every layer (0–15 from top to bottom), shown in Fig. 19, does not increase width depth.

<table>
<thead>
<tr>
<th>Charge Z</th>
<th>Energy Resolution [%]</th>
<th>dE/dx-array @ 200 GeV/amu</th>
<th>TRD @ 1500 GeV/amu</th>
<th>CER @ 1 GeV/amu</th>
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<tr>
<td>1-30</td>
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Fig. 16. Upper panel: Measured energy resolution (1σ) of individual detector subsystems in LDB2 vs charge Z, and for typical energies: Cherenkov: (dash-dot line), dE/dx (solid line) and TRD (dashed line). Lower panel: Comparison of measured energy resolution for the dE/dx array; LDB1 (dotted) and LDB2 (solid).

Fig. 17. Trajectory of two nuclei through a proportional tube. The $\delta$-ray contribution is larger for nuclei passing near the edge of a tube.

Fig. 18. GEANT4 simulation of $\delta$-rays generated by three iron nuclei traversing the instrument. Each point represents an energy deposit by $\delta$-rays in the proportional tubes. The primary ionization tracks of the iron nuclei are not shown.
Because of their large area, the Cherenkov and scintillator detectors are sensitive to \(d\)-rays generated in the overlaying material. These effects have been studied in simulation and discussed in detail previously [24]. The simulation tracks \(d\)-rays until they are stopped or leave the detector, and the contributions to the scintillator and Cherenkov signals are recorded. The result shows that the energy response of the scintillator exhibits a small rise for energies above minimum ionization energy, due to the increased capability of the incident particle to produce highly penetrating \(d\)-rays. This effect is in agreement with that seen in the cosmic-ray data themselves.

**Fig. 19.** Monte Carlo of the average ionization \(\langle dE/dx \rangle\) in the proportional tubes as a function of depth in the instrument. Three incident zenith angles have been simulated.

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**Fig. 20.** Energy response of the Cherenkov counter with and without taking into account the effect of \(d\)-rays.

**Fig. 19.** Monte Carlo of the average ionization \(\langle dE/dx \rangle\) in the proportional tubes as a function of depth in the instrument. Three incident zenith angles have been simulated.

**Fig. 20.** Energy response of the Cherenkov counter with and without taking into account the effect of \(d\)-rays.

5. Data analysis

During the balloon flights, data are collected at rates of 60 and 120 events per second (LDB flights 1 and 2, respectively), amounting to total data volumes of \(5 \times 10^7\) and \(3 \times 10^7\) events for these two flights. The subsequent data analysis determines the properties of each valid cosmic ray event: geometric trajectory through the instrument, elemental charge, and energy (or Lorentz-factor). A number of cuts on the data are necessary to reject ambiguous events and other background. In order to obtain the energy spectra of the different elemental components and the relative abundances, the efficiencies of the data cuts and the geometric acceptance factors have to be known, corrections for particle interactions in the residual atmosphere and in the detector itself need to be made, as well as corrections for mis-identification of particles in charge or in energy must be applied. These procedures have been described in some detail elsewhere [5,6,8]. Hence, we will here only summarize a few key aspects of the data analysis.

5.1. Trajectory reconstruction

The trajectory of each particle through the instrument is obtained from the signals in the proportional tubes (4 double-layers in each of the \(x\)- and \(y\)-directions). Ideally, these provide a set of 16 pulse heights characterizing each cosmic-ray track (not counting spurious signals outside the trajectory). While each tube has a diameter of 2 cm, a fit to just the center positions of the tubes that were hit reveals the trajectory with a lateral accuracy of about 5 mm. A further improvement to \(\Delta x, \Delta y \sim 2 \text{ mm}\) is achieved if one takes into account that the amplitude of each signal is proportional to the path length of the particle through the tube (see Fig. 21). As the figure indicates, there is a left-right ambiguity in the signal for each tube which, however, is readily resolved in the fitting procedure. It should be pointed out that this level of accuracy would not be obtainable for a singly charged particle due to the large Landau-fluctuations in the signal.

5.2. Charge determination

The nuclear charge \(Z\) is determined through a combination of signals from the scintillation and Cherenkov counters. The spatial response of these large counters is not uniform. Therefore, response maps for each PMT are obtained using cosmic-ray muons before each flight.

**Fig. 21.** Track-fitting schematic. The dotted line represents a possible track whose energy deposit would be indistinguishable from the true track if only one layer were analyzed.
For example, Fig. 22 shows the average spatial response map in one quadrant of the scintillator for a single PMT (LDB2). The signals across the counter area are, of course, the largest when the particle impact is closest to the PMT. The discontinuity along the $x=50$ cm line reflects the fact that the scintillator actually is composed of two pieces, separated along this line. As Fig. 5 indicates, each counter quadrant is viewed by 8 PMTs, and each has its own map, analogous to the one of Fig. 22. For each event, the measured 8 signals are individually corrected according to these maps and then summed. The remaining non-uniformity in response across the entire counter area is then $\sim 1\%$, except for 1 cm wide strips along the edges of the counter. Particles hitting these strips are not accepted for analysis.

The response maps are verified with actual cosmic-ray data taken during flight. The response maps, of course, require that the impact points of individual cosmic rays are known from the trajectories as described above. Knowledge of the trajectory also makes it possible to take path length differences, due to varying zenith angles, into account: all signals are normalized to vertical incidence.

Two effects need to be taken into consideration: (a) while for the scintillation, the “energy deposit” is expected to scale strictly with $Z^2$, the “measured signal” increases less strongly due to saturation of the response near the center of the particle track for more heavily ionizing particles. For the charge range relevant to the present measurement, the $Z$-dependence of the signal can be approximated as $\propto Z^{1.65}$. The signals of the Cherenkov counter, however, increase exactly with $Z^2$ (within the measurement accuracy); (b) slight deviations from the Bethe–Bloch behavior of the scintillator, and of the expected $\beta$-dependence of the Cherenkov signal, are observed due to $\delta$-rays accompanying the nuclei traversing the detectors. These effects have been discussed in Section 4.2.

A scatter plot on the correlation of scintillation and Cherenkov signals, shown in Fig. 23 (LDB2), illustrates the separation of the individual elemental species. The figure clearly shows how the Cherenkov signal increases for each element from a minimum signal due to residual scintillation to a maximum when the Cherenkov Counter reaches saturation, while the scintillation signal decreases (according to the Bethe–Bloch formula) and eventually saturates at the level of minimum ionization. Lines of integer charge are defined for each element, such as shown for neon ($Z=10$). By interpolation, each point between the lines is assigned a non-integer charge value and a charge histogram is obtained by summing along lines of constant charge. Fig. 24 shows an example of such a histogram, derived from the scintillator-Cherenkov combination on top of the instrument. The corresponding charge resolution is $\sim 0.3$ and 0.6 charge units for carbon and iron, respectively. For LDB2, the charge resolution could be further improved as identical pairs of scintillator/Cherenkov combinations were installed on top and bottom of the instrument. Fig. 25 illustrates the correlation of the charges identified on top and on bottom for the light elements boron to oxygen.

It should be noted that in principle, also the signal from the proportional tubes could be used for charge identification. However, this is not attempted here as these signals also determine the particle energy, and a bias in the energy measurement could then arise.
5.3. Energy measurement

TRACER measures energies across 4 decades, using the Cherenkov counter (0.3–5 GeV amu⁻¹), the relativistic increase of the ionization signal in the proportional tubes (10–400 GeV amu⁻¹), and the TRD (400–30,000 GeV amu⁻¹).

The low energy measurement with the Cherenkov counter utilizes the steep increase of Cherenkov yield above the threshold of 0.33 GeV amu⁻¹ (see Fig. 2). The energy resolution of the Cherenkov counter is essentially limited by photoelectron statistics and is of the order 5% (see also Fig. 16).

For measurements of higher energy, the signals of the proportional tubes along the particle trajectory are combined as follows:

\[
\frac{dE}{dx} = \frac{\sum_{i=1}^{16} \Delta E_i}{\sum_{i=1}^{16} \Delta x_i} \quad (1)
\]

\[
\frac{dE}{dx} + TR = \frac{\sum_{i=1}^{8} \Delta E_i}{\sum_{i=1}^{8} \Delta x_i} \quad (2)
\]

Here \(\Delta E_i\) and \(\Delta x_i\) refer to energy deposit and path length, respectively, in a tube layer \(i\). If the energy of the particle is below the onset of transition radiation (TR = 0), the two sums become identical, containing 16 measurements of the specific ionization and its relativistic rise. To avoid potentially large fluctuations, signals with \(\Delta x_i < 1\) cm are excluded in the summation. Also, for each event the individual measurement \(\Delta E_i/\Delta x_i\) are required to be consistent with each other within expected levels of fluctuations.

The energy analysis now proceeds as follows: First, particles with energies less than minimum ionization energy are identified via their Cherenkov and \(dE/dx\) signals. Fig. 26 shows the correlation between signals from the \(dE/dx\) counter and the Cherenkov counter for iron nuclei (LDB1). The signals are given in terms of minimum ionization level (MIP) and are normalized by \(Z^2\). The solid line represents the averaged response obtained from simulations including \(\delta\)-rays. The \(dE/dx\) signal decreases towards minimum ionization energy, and then increases in the relativistic region. A cut on the Cherenkov signals, corresponding to the minimum ionization level (MIP/\(Z^2 = 1\)), identifies relativistic particles. As the cosmic-ray energy spectrum falls very steeply, this selection must discriminate against low-energy particles very efficiently. For the events below this cut, the magnitude of the Cherenkov signal is used to determine the particle energy (see Fig. 2), covering the energy range from about 0.8–2.3 GeV amu⁻¹.

For the selected high energy particles, a correlation of the two signals, as defined in Eqs. (1) and (2), is investigated. This analysis is performed for each elemental species separately. As an example, we show in Fig. 27, a scatter-plot of these signals for four elements: oxygen, neon, silicon and iron (from LDB1). The highlighted points illustrate the highest energy events measured with the TRD.
fluctuations become smaller for higher $Z$. Each scatter plot peak at signals corresponding to minimum ionizing particles (MIP) $Z^2 = 1$, with the same signal magnitude for both quantities. With increasing energy, the signals increase at the same rate for both quantities as expected for the relativistic increase in the ionization signal (Fig. 2). Eventually, the TRD shows larger signals than the dE/dx detector. This indicates the appearance of transition radiation at energies above 400 GeV amu$^{-1}$ (Fig. 2). These high energy events are quite rare, and therefore are highlighted in the scatter plot. It is important to notice that these events stand out very clearly, and that there is no noticeable background in other regions of the scatter plot. Considering that the total number of events in the scatter plot for oxygen is about 10$^5$, and is dominated by minimum ionizing particles, one may conservatively estimate the probability of a minimum-ionizing nucleus to be identified as a high-energy TR event to be less than 10$^{-6}$.

The fact that TRACER determines ionization loss and transition radiation in two independent measurements, and that therefore the TR-events are well defined by being off the diagonal in the scatter plot, constitutes a particular strength of the technique. To make sure that only genuine TR-events are accepted for analysis, we typically require that an event has a signal well above the TR threshold.

The energy resolution for the dE/dx events is significantly improved when the gas composition of the proportional tubes was changed for LDB 2. The gas change made possible the energy measurement of the light elements boron and carbon in the dE/dx range. This is illustrated in the lower panel of Fig. 16. The relative improvements are larger for the lighter elements than for iron, where systematic effects contribute.

5.4. Particle interactions in the instrument and in the atmosphere

TRACER measures the intensities of the individual cosmic-ray components at balloon flight altitudes of 4–6 g cm$^{-2}$. However, the intensity of these particles at the top of the atmosphere constitutes the desired astrophysical information. Hence, the measured data must be corrected for losses due to nuclear interactions in the residual atmosphere. Typically, these are spallation interactions where a primary nucleus, with charge $Z$, produces two or more secondary nuclei (and mesons) with charges $Z_i$. The total charge is conserved in the interaction: $Z = \sum Z_i$. The correction for interaction losses is determined using the interaction cross-sections in the Bradt–Peters approximation [25,26]:

$$
\sigma = n\sigma_0(A^{1/3} + A_i^{1/3} - b)^2
$$

with $r_0 = 1.35$ fm, and $b = 0.83$; $A$ and $A_i$ are the mass numbers of the primary cosmic-ray nucleus and of the target atom, respectively. The cross-sections $\sigma$ are assumed to be energy-independent for relativistic nuclei. Systematic uncertainties in the cross-section (of the order of 25%) would therefore result in changes in the absolute intensities of the cosmic rays of the order of a few percent, but would not affect the shape of the energy spectra.

The material of the detector itself also is a target for charge-changing interactions. A computer simulation has determined that the average incident angle of a particle on the detector is 30$^\circ$ and that the resulting average grammage of the detector is $\sim 7.7$ g cm$^{-2}$. Using the detailed composition of the detector material, the interaction probabilities are then calculated. A cosmic-ray nucleus interacting between the top and the bottom part of the instrument will generate inconsistent charge reconstructions on top and bottom, respectively. The bottom charge will appear to be smaller than the top charge because the total scintillator signal of the fragments, with charges $Z_n$, is proportional to $\sum Z_n^n$, and is always smaller than that of the parent nucleus: i.e. $Z^n > \sum Z^n$ for $n > 1$.

Fig. 28 shows a bottom charge histogram for nuclei that are identified, at the top of the instrument, as iron ($Z = 26$). One clearly notices a tail of events with apparently lower charge. These are the interaction products, amounting to approximately 50% of all events, as expected with the numerically determined cross-sections. It should be noticed that Fig. 28 also indicates a small tail of events where the apparent charge at the bottom is slightly higher than the charge on top. These appear to be caused by a small contamination of sub-relativistic iron-nuclei that slow down while traversing the instrument.

To summarize the correction factors for particle interactions, Fig. 29 illustrates the calculated survival probabilities of the individual elemental species in the atmosphere and in the instrument for an average zenith angle of 30$^\circ$.

Finally, it should be noted that daughter nuclei from interactions in the atmosphere cannot be distinguished in the measurement from primary nuclei of the same charge. In practice, this is not a significant contribution to the measurement of the more abundant primary cosmic-ray species, but the effect must be accounted for when the intensities of rare components, for instance boron ($Z = 5$) are determined. For more detail on this issue, see Ref. [8].

5.5. Summary of detection efficiencies

In addition to the interaction losses discussed in Section 5.4, a number of efficiency factors must be taken into account before the absolute cosmic-ray intensities and relative abundances can be quoted. The efficiencies are obtained using the data and

![Fig. 28](image-url)
simulations. The derivation of the efficiencies are discussed in detail in Ref. [6]. Table 5 summarizes the efficiency factors for LDB1 and LDB2.

6. Summary of science results

The balloon flights of TRACER demonstrated that the configuration chosen for this instrument, although novel and unconventional in various respects, can provide clean results on the energy spectra and composition of the heavier cosmic-ray nuclei at energies that could not be reached before, and with record-breaking geometric factors that are required at those energies. The data show convincingly that the measurement technique is capable of clearly identifying the rare particles at the energy range of the TR detector against a background of low-energy particles that may be more intense by four orders of magnitude.

The measurements led to a comprehensive set of new data extending into the region of total energies exceeding $10^{14}$ eV/particle$^{-1}$ for the more abundant species. The maximum energies that could be reached are limited by the available exposure times rather than by intrinsic limitations of the measurement technique. The results are presented in detail elsewhere [6,8], and in the following, we shall just give a brief summary.

In Fig. 30, the absolute intensities at the top of the atmosphere, resulting from the two LDB flights, are plotted for the elements from boron ($Z=5$) to iron ($Z=26$). The intensity of each element is scaled by a factor shown on the left.

These data are compared in Fig. 31 with other measurements of the spectra of primary cosmic-ray elements. Data included for comparison come from measurements in space (HEAO-3 [27] and CRN [28]), on balloons (ATIC [29], CREAM [30], and RUNJOB [31]), and from ground-based measurements with the HESS air-Cherenkov telescope [32]. Data on the light cosmic-ray components $p$ and He, which are not measured with TRACER, are included for completeness. These data come from measurements in space (AMS [33]) and on balloons (ATIC [34], RUNJOB [31], BESS [35,36], CAPRICE [37], and JACEE [38]).

Fig. 32 shows the energy spectrum for iron ($Z=26$) in greater detail, with results from TRACER and from a number of other observations [27–32]. The figure illustrates the variety of detection techniques that have been applied over different, but sometimes overlapping energy ranges, covering an overall range of 4 orders of magnitude in energy and 9 decades in intensity. It is gratifying to notice that all results seem to be quite consistent with each other within the quoted error bars (which, however, are quite large in some cases). At low energies, the TRACER 2006 data
with limited by two effects: (1) the scintillator signal does not scale
factor of the instrument. However, the capability of the system is
chosen in order to minimize weight and to optimize geometric
tubes via wavelength-shifting bars. This arrangement had been
and plastic Cherenkov counters, all read out with photomultiplier
the signals of two double-layers of rather thin plastic scintillators
Recall from Section 5.2 that the charge measurement is based on
consider the resolution in charge
the TRACER system could be further enhanced, one would have to
TRACER, would be scientifically highly rewarding.

7. Future prospects and conclusions

The experimental configuration chosen for TRACER has proven to
be well suited and sufficiently rugged for use in long-duration
balloon flights at polar latitudes. In particular, the proportional tube
array operates stably at external pressures of a few millibar without
problems due to high-voltage corona, without significant gas-leaks,
and without deterioration due to gas poisoning on the time scale of
weeks. The tube array and its read-out electronics provide linear
signals over a dynamic range of several 10^3 above noise, and the
tube signals lead to remarkably good spatial resolution (≈ 2 mm)
for cosmic-ray trajectories. The entire instrument operates at
ambient pressure (excluding a small pressurized volume for sensi-
tive components such as high-voltage supplies and disks for data
storage), but maintains comfortable temperatures during flight
without signs of local overheating or excessive cold spots. The major
limitation in the scientific results is counting statistics during the
limited exposure time. There is every reason to predict that addi-
tional LDB flights, or even an exposure in space of an instrument like
TRACER, would be scientifically highly rewarding.

Nevertheless, if one asks the question whether the response of
the TRACER system could be further enhanced, one would have to
consider the resolution in charge Z that has been accomplished.
Recall from Section 5.2 that the charge measurement is based on
the signals of two double-layers of rather thin plastic scintillators
and plastic Cherenkov counters, all read out with photomultiplier
tubes via wavelength-shifting bars. This arrangement had been
chosen in order to minimize weight and to optimize geometric
factor of the instrument. However, the capability of the system is
limited by two effects: (1) the scintillator signal does not scale
with Z^2 and therefore, the resolution in Z decreases with increas-
ing charge number (see Fig. 24); (2) the number of photo-
electrons detected from the Cherenkov-counters is relatively
low (see Section 3.1); hence, photoelectron-statistics affects the width of Cherenkov-signal distributions.

An improvement in charge resolution would be particularly
helpful for cosmic-ray composition measurements that aim to
obtain the intensities of secondary cosmic-ray nuclei (i.e. those
produced by spallation in interstellar space), relative to the
intensities of their primary parent nuclei. Such measurements are
very important for understanding the propagation of cosmic rays
through the Galaxy. There are two charge regions of secondary
nuclei: the light elements Li, Be, and B; and the heavier nuclei just
below iron, Sc, Ti, V, Cr, and Mn. TRACER in its present conﬁgura-
tion can measure the lighter nuclei, in particular, boron (Z = 5), and
results on the abundance of boron, relative to the parent elements
carbon and oxygen at high energies have been submitted for
publication [8]. However, the charge resolution is insufficient for separation of the sub-nuclei ions. This short-coming can be removed with an improvement in the Cherenkov counter system.

We may consider replacing the top Cherenkov counter with a pair of Cherenkov counters, one using an aerogel radiator, and the other an acrylic counter, both in light collection chambers which collect light more efficiently than the present counter, and hence, improve the photo-electron statistics. The signals in both counters are strictly proportional to $Z^2$, and the low index of refraction of aerogel provides an energy measurement over a larger range of energies above the minimum-ionization level. The charge resolution would then be independent of charge. This technique has been successfully utilized in the balloon borne Trans Iron Galactic Recorder (TIGER) instrument [39].

Monte Carlo simulations have shown that a charge resolution of 0.2 charge units could be obtained with the proposed Cherenkov counter system [40,41]. Fig. 33 shows the results from a simulated charge reconstruction for such a setup. The upper panel shows a cross correlation plot of the simulated signals from the aerogel and acrylic counters. Each vertical line represents cosmic rays of a given charge number. The resulting charge histogram, shown in the lower panel of Fig. 33, indicates that the sub-Fe elements are clearly resolved.

If TRACER were equipped with such an improved Cherenkov system and exposed for several weeks, measurements of all the secondary cosmic-ray nuclei well into the region of several TeV amu$^{-1}$ could be achieved, as well as much extended results for the primary nuclei.

Acknowledgments

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Appendix A. Proportional tube construction

The body of the proportional tube (1), as shown in Fig. 34, is constructed from three layers of spiral wound Mylar. The inner layer is 0.002 in. aluminized Mylar, while the outer layers are 0.001 in. thick. The tubes are manufactured by Electrolock, Inc. of Chagrin Falls, OH.

The construction of the complete tube system proceeds as follows (see Fig. 34): A commercial thin aluminum cylinder (actually, the end of an aluminum cigar tube which is exactly 2 cm in diameter) is glued into the Mylar tube (2,3) at each end. A 0.002 in. diameter stainless steel wire (California Fine Wire Company) is tensioned to 70 lbf and held on the wire-holder between two washers. A small G-10 pad (6) serves as interface between the sense wire and the high-voltage/signal wire that exits the tube through the neck of the end-cap (4), also made from glass-filled Noryl. This end-cap has an O-ring, which forms a seal with a gas manifold that services tubes with gas and high voltage. The other end-cap has a barb fitting for a Tygon hose. Both endcaps are potted into the cigar tube assembly with RTV 21 (General Electric).

Appendix B. Details of thermal protection

A complete thermal model of TRACER was developed using the SINDA heat transfer design package by C&R Technologies. The model was run in a number of extreme conditions for each flight (Cold case—night time with low albedo; Hot case—day time with high albedo). The model indicated that a passive thermal configuration was well suited for TRACER. A multi-layer insulation, with low overall thermal conductance, that traps heat generated by the instrument was developed. This was achieved by choosing materials that have a combination of low radiation absorptivity ($\alpha$), high emissivity ($\varepsilon$) on its exterior surface, and low thermal conductance ($k$) between layers. The configuration was as follows:

An external layer of aluminized Mylar (76 $\mu$m, $\alpha = 0.17$, $\varepsilon = 0.76$), with the aluminized side on the inside, reflects solar radiation. The middle insulating layer consists of 4 inches of FALCON foam type I ($k = 0.0314$ W m K$^{-1}$). Finally, the inner-most layer is used to trap and redistribute heat generated by the instrument and is made from aluminum foil (3 $\mu$m thick). The aluminum foil has high heat reflectivity ($\alpha = 0.20$, $\varepsilon = 0.03$), high thermal conductivity, and as it is electrically conductive it also acts as a Faraday cage for the payload.

For the coldest thermal environment ($T_99$), the payload was completely enclosed on all sides by the insulation. For the hottest thermal environment (LDB1), the insulation around the lower level of TRACER was replaced with a thin sheet of aluminum (3 mm). This is necessary to allow the major heat producing elements such as the pressurized vessel and flight control systems to radiate to the external environment. The aluminum was painted white (Sherwin-Williams Inc. #141-4416; $\alpha = 0.314$, $\varepsilon = 0.81$) to prevent localized heating of exposed metal, and the external side of the aluminum was coated with a silverized Teflon tape (Sheldahl Inc. #146401 5 mil (127 $\mu$m), $\alpha = 0.08$, $\varepsilon = 0.81$). The Teflon tape is very efficient in allowing heat to transfer out of the instrument while still maintaining a high reflectance of...
For LDB2, the overall thermal environment is cooler than for LDB1 in Antarctica, but warmer than for the continental flight T99. Hence, the thermal insulation used for LDB2 is the same as for LDB1, except that the silverized Teflon tape is replaced with aluminized Mylar.

References