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Antarctic Balloon Flight and Data Analysis of TRACER

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The TRACER cosmic-ray detector was successfully flown from McMurdo, Antarctica in December 2003. The instrument has a geometric factor of 5 m^2 ster and provided measurements of cosmic ray nuclei from oxygen to iron (Z=8 to Z=26). The analysis of the data begins with the reconstruction of the trajectory of each nucleus through the instrument. Subsequently, the elemental charge Z and the particle energy are measured from 0.5 to 10,000 GeV/amu. This process uses known response functions and fluctuations in response of the individual detector elements, and the procedures are verified with extensive computer simulations. The analysis is able to cleanly select the very rare events at the highest energies without contamination due to low energy background which is more abundant by about a factor of $\sim 10^4$.

1. Introduction

The concept of the TRACER instrument for the detection of high-energy cosmic-ray nuclei was first demonstrated with a successful test flight from Fort Sumner, NM in 1999 [1]. To obtain data with much improved statistics, a long-duration balloon (LDB) flight is required, and was conducted from McMurdo, Antarctica in 2003, at the first opportunity when a launch vehicle compatible with the weight of TRACER (∼1600kg) was available at that site. The LDB flight yielded a total exposure of 50 m^2 ster days at an average altitude of 3.9 g/cm^2. In contrast to Fort Sumner, the high geomagnetic latitude at McMurdo exposes TRACER to a large flux of low energy particles. The instrument must therefore avoid the mis-identification of low energy particles while retaining high efficiency for the detection of the rare high-energy events. Keeping this requirement in mind, the analysis procedure aims at identifying the particle species with single charge resolution and measuring the particle energy E, or Lorentz factor γ=E/mc^2, over four orders of magnitude.

2. Analysis Procedure

The data analysis proceeds by first determining the trajectory of each cosmic-ray particle through the detector system, then determining charge Z and energy E for each event, and finally, evaluating all efficiency losses due to the various cuts in the data. Monte Carlo simulations are necessary to test and refine the data analysis procedure. Extensive simulations of the TRACER detector as well as other analytical tools have been developed that run in parallel with each step in the analysis procedure. Wherever possible, the results of the simulations are verified with the measured data themselves.

2.1 Simulations

The TRACER simulation code (TSIM) is a GEANT4 [2] based simulation of the detector. The code includes the geometry of the individual instrument components and uses the "G4hIonisation" model of the energy deposited and δ-ray production in each part of the detector. The program generates a simulated cosmic-ray

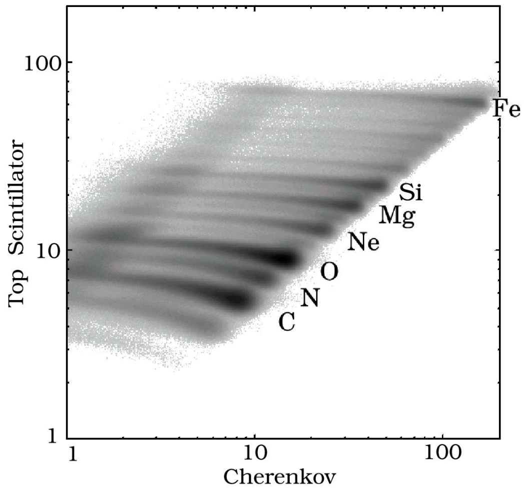

Figure 1. Scatter plot of top scintillator vs. Cherenkov signal in arbitrary units.

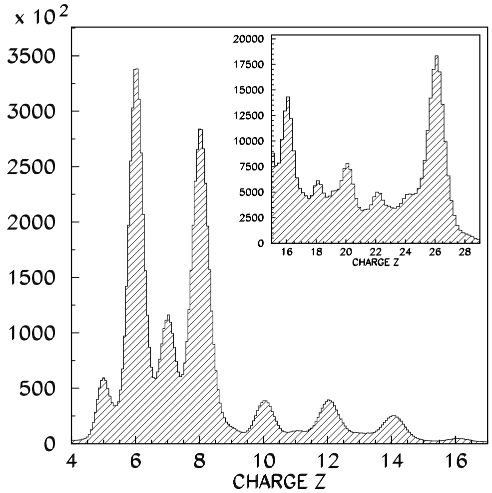

Figure 2. Charge histogram for all events measured in flight.

data set, which is then subjected to the same analysis procedures as the real flight data. In addition, simpler simulations have been developed to model fluctuations in the detector and δ-ray effects where TSIM was found to be impractical.

2.2 Trajectory Reconstruction

Each particle travels through sixteen layers of 2cm diameter proportional tubes (see figure 1 in [3]). These are oriented in two orthogonal directions and thus provide all details about the particle trajectory. Using the positions of the centers of all tubes that show signals above threshold, a first estimate of the trajectory is obtained. Due to the cylindrical shape of the tubes, the pathlength through each tube along the particle trajectory is generally different. However, the signal amplitude measured in each tube is proportional to the pathlength within statistical fluctuations. This fact is applied to determine a refined track fit. The average total pathlength through all tube layers is 24 cm for particles incident within the acceptance cone of the instrument.

Including the geometry of the proportional tube array in the simulation, the tracking accuracy is determined by comparing the simulated track with the track reconstructed by the analysis routine. Typically, the recontructed track has an accuracy of 2mm in the impact parameter, and 8 mm (3 %) for the total pathlength through all tubes. The tracking efficiency is determined by counting the number of simulated events that pass the track quality cuts. The tracking efficiency is 95%.

2.3 Charge Identification

The charge of a particle traversing the instrument is determined primarily from the scintillator signals. Note that the scintillators are only 5 mm thick. Their response exhibits spatial non-uniformities which are mapped with muons on the ground and with flight data. The response maps, together with the trajectory information, are used to correct the signal for each event. The presence of low energy particles, with signals larger than

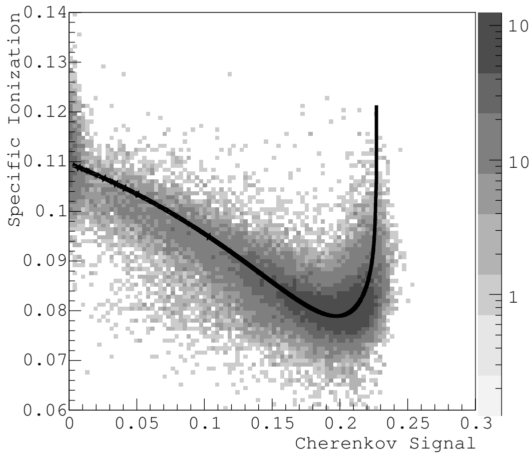

Figure 3. Scatter plot of dE/dx vs. Cherenkov signals for iron nuclei. The black line is the average response obtained from simulations. The units are arbitrary.

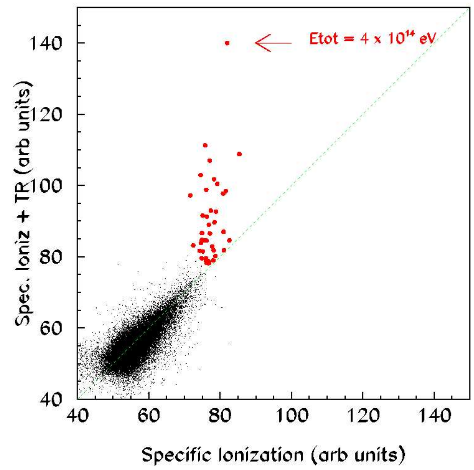

Figure 4. Scatter plot of TR vs. dE/dx signal for iron nuclei. The units are arbitrary.

minimum ionization, requires to combine the scintillator signals with an energy scale; otherwise the charge resolution from scintillator measurements becomes smeared out. This scale is provided by the Cherenkov counter signal. Figure 1 shows the correlation plot of top scintillator signal vs. Cherenkov signal. From this scatter plot lines of constant charge are identified. By summation along these lines the charge histogram shown in figure 2 is obtained. The charge resolution (1σ) is 0.3 charge units for oxygen and 0.5 charge units for iron.

2.4 Energy Measurement

The energy measurement results from the combination of three types of detector covering a range of 0.5 GeV/amu to 10,000 GeV/amu: The Cherenkov counter measures the energy of a particle from 0.5 GeV/amu up to saturation around 10 GeV/amu. For higher energies the energy is obtained from the measurement of the specific ionization and its relativistic rise in the top eight layers of proportional tubes (dE/dx), or the detection of x-ray transition radiation in the bottom eight layers of proportional tubes (TRD). (For details of the configuration see [3].) To find the average dE/dx the signal ΔE_i in each tube along the particle trajectory is taken along with the corresponding pathlength Δx_i in the tube. The summation dE/dx=$\sum \Delta E_i / \sum \Delta x_i$ gives the overall value of the specific ionization. In this summation, the tubes with small pathlengths, Δx_i <1cm, are excluded since fluctuations in the signal increase for shorter pathlength. The average TR signal is found in the same manner using tubes in the TRD layers.

With simulated data generated by TSIM the signal fluctuations in the proportional tube array are determined and compared to the fluctuations measured from the data. For instance, for iron the measured dE/dx fluctuations are 3% while the simulated fluctuations are 2%. The increase in the measured value is due to the tracklength uncertainty (∼3%, see section 2.2). Hence, simulations and data agree quite well.

The energy deposit in a gas proportional tube is described by the Bethe-Bloch formula. It is degenerate in energy: a signal larger than minimum ionization could either be generated by a low-energy particle, or could be elevated due to the relativistic rise in dE/dx with energy. To break the degeneracy the energy scale provided by the Cherenkov counter is used. Figure 3 shows a scatter plot of dE/dx vs. Cherenkov signals for iron nuclei. The correlation follows closely the pattern predicted by simulations [3]. With the combined signals of dE/dx and Cherenkov the minimum ionization point in the dE/dx signal is identified, and the corresponding Cherenkov signal distinguishes between low and high energy particles. The Cherenkov signal provides an energy measurement for particles below the minimum ionization energy.

Simulations have been used to study the effect of δ-rays generated while the particle traverses the detector. It is found that δ-ray contributions on proportional tube signals are negligible; however, they produce increased signals in the large-area scintillator and Cherenkov counters at the bottom of the instrument [4]. The effects of δ-rays are taken into account in the analysis and are verified with the data.

To measure the energy of a particle at higher energies, above 10 GeV/amu, the combined responses of TR and dE/dx are used. Figure 4 shows the correlation of the TR signal with the dE/dx signal for iron data. For events with energies below 400 GeV/amu, the onset of transition radiation, the signals are well correlated along the diagonal. The energy assigned to these events is obtained from a parameterization of the relativistic rise in the energy deposited in a gas tube [3]. Signals at energies higher than 400 GeV/amu have a significant contribution from transition radiation and are identified on the scatter plot in figure 4 by their location above the diagonal. The events are assigned an energy according to a parameterization of the TR response curve [3]. Note that these rare events at the highest energies (representing a fraction of the order of 10^{-4} of all detected iron nuclei) stand out in the scatter plot without any significant contribution of background.

The signal fluctuations for each component of the detector depend on the charge of the particle and its energy. For example, the corresponding energy resolution of the Cherenkov counter measurement for iron is 20% at 3 GeV/amu, but 40% with dE/dx at 20 GeV/amu and $<$10% for the TRD at 1,000 GeV/amu.

3. Conclusions

The long-duration balloon flight of TRACER has provided a statistically significant data set of cosmic ray nuclei from oxygen to iron up to TeV/amu energies, or even beyond. High energy events are clearly discriminated against the low energy background. The measurements cover four decades in energy with single charge resolution. The resulting energy spectra are presented in [5].

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