Measurement of the absolute charge of cosmic ray nuclei with the AMS Transition Radiation Detector

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Abstract: The AMS-02 Transition Radiation Detector, TRD, is designed to use transition radiation to distinguish positrons from protons, and dE/dx to identify light nuclei. Capabilities of the TRD for measuring charge of heavy nuclei are significantly extended by using a novel reconstruction technique which is based on measuring the number of delta-electrons emitted by relativistic nuclei inside the TRD. Analysis of on-orbit data shows that heavy nuclei up to Fe can be identified using this approach. We present this technique which significantly extends AMS-02 capabilities in probing cosmic nuclei physics.

Keywords: AMS, cosmic ray nuclei, delta ray, particle identification.

1 Introduction

Cosmic ray nuclei are charged particles reaching the earth's atmosphere from all directions. The nuclei generated before propagation are called primary cosmic ray nuclei. Hydrogen and Helium are produced in the Big Bang Nucleosynthesis, which also generates trace amount of Deuteron and Lithium. Heavier elements from Carbon to Nickel are synthesized by nuclear fusion during stellar evolution. The elements with nucleon number larger than 56 are typically produced in supernova explosions. Secondary cosmic ray nuclei are produced from the spallation of primary cosmic ray nuclei when propagating in the interstellar medium, examples are Lithium, Beryllium and Boron. The production, propagation and acceleration of cosmic ray nuclei contain a wealth of information on astrophysics, particle physics, and nuclear physics. Measurements of properties of cosmic ray nuclei with very high accuracy are of crucial importance in advancing understanding in these fields. For example, energy spectra of primary cosmic ray nuclei fluxes provide key information of cosmic ray acceleration mechanism; abundance ratios of secondary over primary cosmic ray nuclei, such as Boron-to-Carbon ratio, are excellent probes for cosmic ray propagation in interstellar medium; abundance ratio of primary Lithium over Hydrogen largely depends on the Baryon asymmetry parameter in the Big Bang Baryogenesis. AMS-02 is capable of making high precision measurements of cosmic ray nuclei that have not been done before. These have the potential of making significant discoveries in unexplored regions.

To make these discoveries possible, strong capabilities of identifying the absolute charge of detected particles are necessary for AMS [1]. Cosmic nuclei are totally ionized by going through space and materials in top part of AMS. Multiple subdetectors in AMS provide redundant measurements of particle charge, as well as the ability to identify charge changing processes due to nuclear interactions inside the detector. Nine layers of the Silicon Tracker and four layers of Time of Flight (TOF) scintillators measure charge with the particle's energy loss in the detector to very high resolutions ($\sigma_{Charge} \approx 0.1$ for light nuclei); The Ring Imaging Cherenkov (RICH) detector measures charge by the number of Cherenkov radiation photons emitted by the particle when passing through radiator. The Transition Radiation Detector (TRD) is on top of the instrument, so its charge measurement plays a significant role in identifying and controlling the effects of charge changing nuclear interactions in AMS. In this paper, we demonstration the ability of the TRD in identifying particle charge by energy loss of the particle as well as a novel technique of counting delta rays produced inside the TRD.

2 The AMS transition radiation detector

The AMS TRD [2] consists of 20 layers of 20 mm fleece radiators and 6 mm drift tubes filled with Xe and CO_2 working at proportional mode. Electrons are produced by ionization of charged particles, they are drifted in the gas towards the wire positioned at the center of the tube with a certain high voltage. To compensate the gas gain change due to gas diffusion across the tube wall, a daily high voltage adjustment is performed, and the gas is refilled every month [3].

To push the TRD towards the extreme of its performance, dedicated dynamic alignment [3] and gain calibration [4] are performed based on the flight data on-board the International Space Station (ISS). Because of the complex thermal environment on-board the ISS, the supporting structure of the TRD suffers from expansion and contraction, leading to the movement of the TRD with respect to the detector coordinate system defined by the Silicon Tracker. This influences the path length calculation and thus particle identification capability. The time dependent alignment is done by minimizing the residual distance between the particle track reconstructed by the Silicon Tracker and tubes passed by charged particles. As mentioned above, gas gain is constantly changing due to gas diffusion, so gain calibration is vital for obtaining reasonable ionization signal and hence the power of particle identification. Gain calibration factors are obtained by fitting the minimum ionizing particle ADC spectra from cosmic protons as well as overall exponential ADC spectra from general radiation in space. A dedicated smoothing procedure based on Kalman filter is applied to the gain corrections, this reduces the time dependent uncertainties.

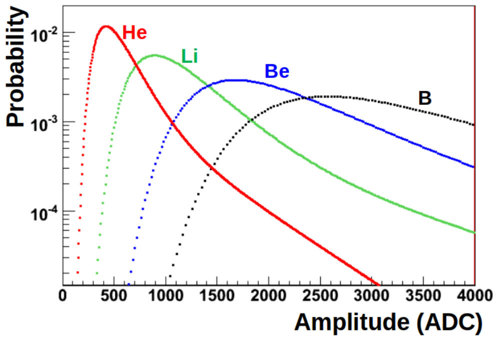

Figure 1: dE/dx PDFs of Helium, Lithium, Beryllium, and Boron, derived from flight data.

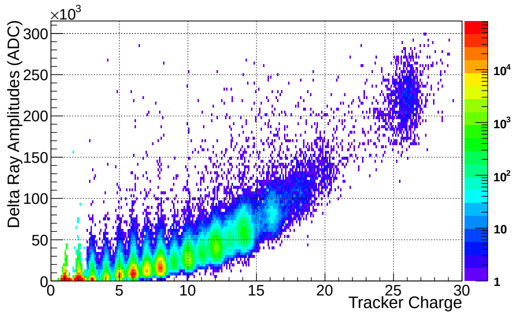

Figure 2: Delta ray amplitudes as a function of the charge measured by the Silicon Tracker.

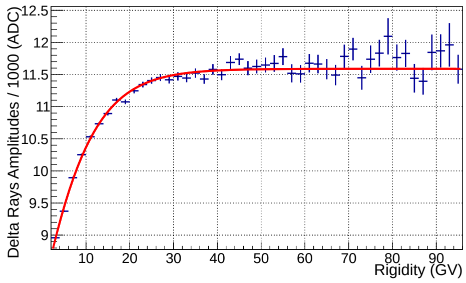

Figure 3: Delta ray amplitudes as a function of rigidity for Z = 6 particles measured by the Silicon Tracker and the Time of Flight.

3 Reconstruction of the absolute charge of cosmic ray nuclei with the TRD

Traditionally, the dependence of dE/dx on particle charge, Z, is used to do charge measurements. The energy loss is also dependent on path length and rigidity. We parameterize the distributions of energy loss in each tube as analytical functions of these variables, the analytical functions are called dE/dx Probability Density Functions (dE/dx PDFs), which will be used in determination of Z in a likelihood method described below. Figure 1 shows representative dE/dx PDFs of Helium, Lithium, Beryllium, and Boron. The PDFs can only be made at discrete integer charge, we use cubic spline interpolation to extend the parameters in the PDFs to functions of continuous charge. The dynamic ADC range for the TRD is around 3400 bins above pedestal with 4096 bins from a 12 bit ADC, this characterizes a typical signal of minimum ionizing Boron or Carbon with average path length. Therefore, for particles with Z larger than 6, the ADC readout is saturated. To extend the measurements to particles with higher charge, as well as increase the resolution for light ions, new techniques are developed.

Besides dE/dx, additional information of the produced delta rays can also be utilized for charge measurements. When charged particles pass through the TRD, the produced keV scale delta rays travel almost perpendicular to the particle velocity, and some of them can be detected by the drift tubes not passed by the ions but in the vicinity (a few cm) of the particle track. We tag these tubes as delta ray tubes, whereas the tubes passed by ions are defined as dE/dx tubes. The signals in delta ray tubes are typically far below the ADC saturation threshold. Particles with higher Z corresponds to more delta rays, hence a higher ADC signal in delta ray tubes. Figure 2 shows the average signal in delta ray tubes as a function of charge measured by the Silicon Tracker, Clear differences of signals between different ion species can be seen. The dependences of delta ray tube amplitude on layer and inclination are studied and no obvious dependence is found. However, the delta ray tube amplitude does change with increasing energy of the incoming particle. Figure 3 plots the amplitude as a function of rigidity for Z = 6 particles selected by the Silicon Tracker and Time of Flight, from which we observed the number of delta rays increases with rigidity for rigidity below 25 GV, and is almost constant in higher rigidity ranges. Similar to dE/dx PDFs, we get Delta Ray PDFs by parametrization on delta ray tube amplitude distributions.

Delta ray tubes and dE/dx tubes are mostly adjacent to each other, for particles with high energy, these two categories of tubes can be distinguished by calculating path length from extrapolated Tracker track, but this is not accurate for low energy particles due to multiple scattering. Therefore, a dedicated track fitting algorithm with the TRD is developed, and a pointing accuracy of about 400 microns is reached.

We construct likelihood functions based on dE/dx PDFs and Delta Ray PDFs, and combine them into a global likelihood function. By maximizing the likelihood function, we find the most probable charge value:

$$\begin{aligned} L_{dE/dx}(Z) &= \sum_i log_{10}[f^i_{dE/dx}(Z;\vec{X}_i)] \\ L_{DeltaRay}(Z) &= log_{10}[f^{Total}_{DeltaRay}(Z;\vec{X}_i)] \\ L_{Total}(Z) &= L_{dE/dx}(Z) + L_{DeltaRay}(Z) \\ \frac{dL_{Total}(Z)}{dZ}|_{Z=Z_0} &= 0 \\ \Rightarrow \quad Z_0 &= TRD\ Charge \end{aligned}$$

Where f are the probability density functions, $\vec{X}_i$ stands for a set of parameters for a given fired tube, and i goes through all tubes passed by the charged particle. The likelihood function can be well approximated using a parabola function around the maximum point, based on this fact we developed a fast maximizing algorithm, which is orders of magnitude faster than the TMinuit package in ROOT. The error of the measured charge is calculated by decreasing the maximum likelihood value by 0.5 and find the shift in Z value.

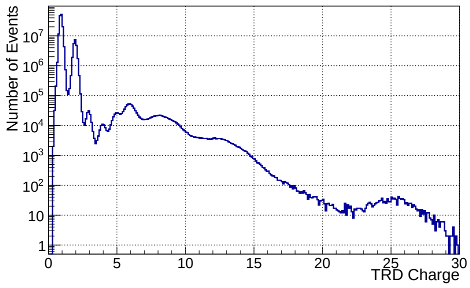

Figure 4: Distribution of charge of cosmic ray nuclei measured by the TRD alone.

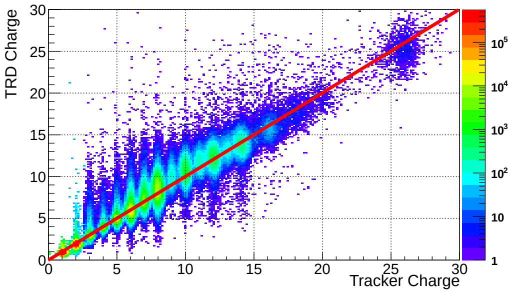

Figure 5: Comparison between charge measured by the TRD and charge measured by the inner Silicon Tracker.

4 Performance of identifying cosmic ray nuclei with the TRD

The performance of the TRD charge reconstruction algorithm can be studied using the ISS flight data. Figure 4 shows the distribution of charge of cosmic ray nuclei measured by TRD, from which we can clearly see peaks from Z = 1 to Z = 6, for Z > 6, even though the ADC readout of dE/dx tubes are saturated, the charge measurements can be extended to Z = 26 with the information of delta rays. The delta ray tubes for Z = 26 are still far away from saturation threshold, so in principle with this approach we can measure particles with even higher charge, but quality of Delta Ray PDFs are somewhat limited by statistics.

Figure 5 plots the comparison between charge measured by the TRD and charge measured by the inner Silicon Tracker, from Z = 1 to Z = 26. Good agreements are observed.

In future, by reducing the high voltage, the gain can be diminished dramatically, thus the suffering from ADC saturation is reduced, and the charge measurements for particles with Z > 6 with the TRD could be largely improved. With such operations, in addition, transition radiation photons from nuclei can be measured to determine particle's energy at scale of 10 TeV. Considering the TRD's large acceptance, the long operation time of AMS on the ISS, and the fact that the maximum detectable rigidity using the AMS Silicon Tracker is about 2 TeV, this could significantly extend the energy range of spectra measured by AMS.

5 Summary

The TRD of AMS is able to identify light cosmic ray nuclei by measuring dE/dx within its ADC dynamic range, and the measurement can be improved and extended to higher Z using a novel approach by counting the number of delta rays produced in AMS. After dedicated dynamic alignment and gain calibration, PDFs are made for both dE/dx tubes and delta ray tubes, by a likelihood method the two kinds of information are combined. The performance studied from ISS flight data shows heavy nuclei up to Fe can be identified.

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