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Light nuclear charge measurement with Alpha Magnetic Spectrometer Electromagnetic Calorimeter

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ABSTRACT

The Alpha Magnetic Spectrometer (AMS) is a high energy particle detector installed and operating on board of the International Space Station (ISS) since May 2011. So far more than 70 billion cosmic ray events have been recorded by AMS. In the present paper the Electromagnetic Calorimeter (ECAL) detector of AMS is used to measure cosmic ray nuclear charge magnitudes up to $Z=10$. The obtained charge magnitude resolution is about 0.1 and 0.3 charge unit for Helium and Carbon, respectively. These measurements are important for an accurate determination of the interaction probabilities of various nuclei with the AMS materials. The ECAL charge calibration and measurement procedures are presented.

1. The AMS detector

AMS is a general purpose high energy particle physics detector in space. The layout and description of the detector are presented in [1–3]. The key elements used in this analysis are a permanent 0.15 T magnet [4], a silicon Tracker, four planes of time of flight (TOF) scintillation counters, and an electromagnetic calorimeter (ECAL). AMS also contains a transition radiation detector (TRD), a ring imaging Cherenkov detector (RICH), and an array of 16 anticoincidence counters (ACC).

The AMS coordinate system is concentric with the magnet. The x axis is parallel to the main component of the magnetic field and the z axis points vertically. The (y–z) plane is the bending plane. Above, below, and downward-going refer to the AMS coordinate system.

The Tracker [5] has nine layers, the first (L1) at the top of the detector, the second (L2) just above the magnet, six (L3–L8) within the bore of the magnet, and the last (L9) just above the ECAL. L2–L8 constitute the inner Tracker. The Tracker accurately determines the cosmic ray trajectories by multiple coordinate measurements. Together, the Tracker and the magnet measure the rigidity R of charged cosmic rays. For $Z=2$ to $Z=10$ particles, the spatial resolution in each Tracker layer ranges from 7.5 μm in the bending direction. The maximum detectable rigidity (MDR) is 2 TV to 3.2 TV over the 3 m lever arm from L1–L9. Each Tracker layer also provides an independent measurement of cosmic ray charge Z. Together, the charge resolution of the inner Tracker layers is $\Delta Z \simeq 0.07$ for $Z=2$ and $\Delta Z \simeq 0.1$ for $Z=8$ particles.

Two planes of TOF [6] counters are located above L2 and two below the magnet. The overall velocity ($\beta = v/c$) resolution has been measured to be $\Delta\beta/\beta^2 = 0.02$ for $Z=2$ to $Z=10$ particles, allowing an efficient discrimination between upward- and downward-going particles. The pulse heights of the two upper layers are combined to provide an independent measurement of the charge with an accuracy $\Delta Z \simeq 0.08$ to $\Delta Z \simeq 0.12$. The pulse heights from the two lower planes are combined to provide another independent charge measurement having the same accuracy.

2. Event selection in AMS ECAL

The AMS Electromagnetic Calorimeter (ECAL) [7] is a thick lead scintillating fibre sampling calorimeter of 17 radiation lengths. It is composed of a sandwich of 9 superlayers whose scintillating fibres alternate in x and y directions to allow for a three-dimensional imaging reconstruction of the longitudinal and lateral shower development. The light guided by the fibres is read out by 4-anode Hamamatsu R7600 00-M4 photomultipliers (henceforth PMT, each anode defining a cell). To avoid dead zones, for each superlayer 36 PMT are alternatively distributed at each end of the fibres, for a total of $4 \times 9 \times 36 = 1296$ read-out channels. All the PMT read-out signals are equalized with respect to light attenuation and gain

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corrections using beam-test and ISS data signals from protons and He particles.

2.1. Charge measurement through ionization energy loss

The primary mode of hadron interaction in the ECAL before the shower development is through ionization, characterized by the absence of lateral spread of energy deposition, and whose mean energy loss is well described by the Bethe–Bloch equation [8]

$$\left\langle -\frac{dE}{dx}\right\rangle = KZ^2 \frac{Z_0}{A}\frac{1}{\beta^2}f(\beta) \quad (1)$$

where Z is the charge of the incident particle, Z_0 is the absorber charge, A is its atomic number, β is the particle relative velocity and K is a constant. The strong dependence of ionization energy loss on incident particle charge ($dE/dx \sim Z^2$) is used for charge measurement in ECAL.

2.2. Event selection

The sample selection consists of downward-going events with a reconstructed Tracker track of charge not compatible with unity, a velocity measured by the TOF, $\beta > 0.4$ and a shower (collection of hits) in the ECAL. The track reconstruction quality is provided by requiring at least 5 hits in the inner Tracker and 1 in L9, with a track fit quality $\chi^2/d.f. < 10$ in the bending coordinate. The compatibility of the charges measured by inner Tracker and L9, ensures the absence of nuclei interaction above ECAL. Finally, the distance between ECAL shower center and Tracker extrapolated position must be smaller than 2 cm, in both x and y directions, warranting the geometry match of reconstructed track and ECAL shower. Hence the particles crossing ECAL have precise position, direction and rigidity measurements. Particular nuclei samples are then selected using combined inner Tracker and Tracker L9 charge measurements.

The charge measurement uses the ECAL layers crossed by particles interacting only through ionization (without lateral spread of energy deposition). In each layer the cell with largest energy deposition (called $S1$) is selected from 5 cells around the AMS Tracker extrapolated coordinate. $S3$ is defined as the sum of $S1$ and the energy deposition in its two adjacent cells, if they exist. $S5$ is likewise defined as the sum of $S3$ and the energy deposition in its two adjacent outer cells, if they exist.

The $S3/S5$ ratio is used to control the incident particles lateral spread, and is required to be greater than 0.9. Fig. 1 shows the typical distributions of $S3/S5$ for He and C nuclei. To select ECAL layers without fragmentation, the total energy deposition in a layer is required to be consistent with the one in the layers above it.

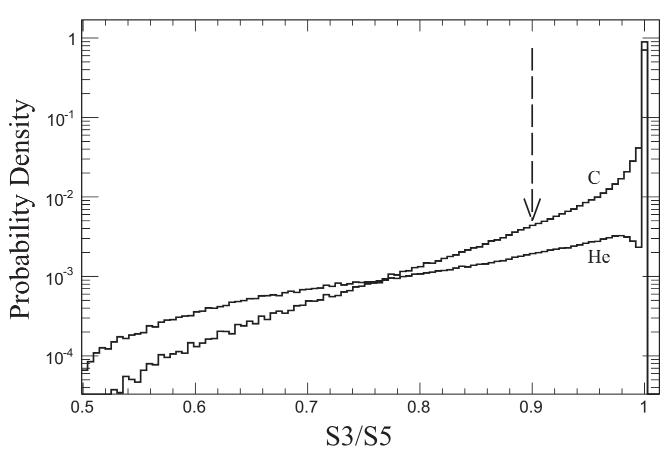

Fig. 1. The $S3/S5$ ratio distribution for He and C in ECAL layer 1. In this work $S3/S5$ must be greater than 0.9 to select non-interacting nuclei.

3. ECAL charge calibration

Four additional corrections are implemented before achieving the final ECAL charge estimator, including PMT efficiency, Birks saturation effect, path length and rigidity dependence.

3.1. PMT efficiency correction

The PMT efficiency depends on the light incident position in a PMT cell. Generally, the PMT efficiency is high near the cell center and low near the edges. The equalization of the PMT response requires a detailed knowledge of the light incident position, provided by the Tracker extrapolation of the incident position in the ECAL cell.

After aligning ECAL and Tracker, the geometric symmetries of PMT response are used to extract the ECAL residual misalignment; both the x and y residual shifts are then below a few tens of μm. The most probable value of the PMT response for a given position is evaluated through a fit by the function (2):

$$F(x) = Ae^{-s_2(\nu + e^{-\nu})} \quad (2)$$

where $\nu = \frac{x-\mu}{s_1 s_2}$, μ denotes the most probable value, s_1 and s_2 are parameters characterizing the attenuation of probability density. One typical fit can be seen in Fig. 2. This fit typically has χ^2/ndf of 38.5/29.

Fig. 3 shows the obtained dependence of energy deposition on the particle incident position for Helium nuclei. The response differences between cell center and edge can amount to $\sim 40\%$. The data is parameterized with a polynomial fit to perform the efficiency correction; the resulting PMT response in different cell ranges become flat, see Fig. 4.

3.2. Birks saturation effect

The PMT efficiency correction allows the linearity of ECAL response to be checked for different nuclei, as can be seen in Fig. 5. The non-linearities, visible above $Z=6$, are due to recombination and quenching effects between the excited molecules and the surrounding substrate [9,10]. Dense ionization columns emit less light than expected on the basis of dE/dx for minimum ionizing particles [8], preventing organic scintillators from responding linearly to ionization density. This so-called Birks saturation effect,

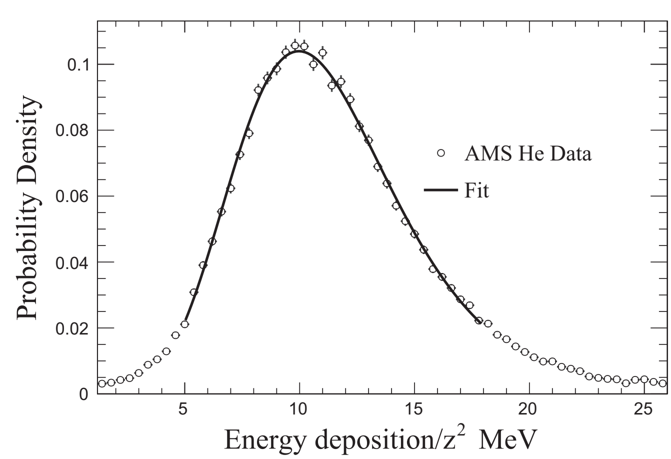

Fig. 2. A typical fit by Eq. (2) for Helium in ECAL layer 2 at relative cell position -0.25, $\mu = 9.97 \pm 0.036$, $s_1 = 2.67 \pm 0.113$, $s_2 = 1.66 \pm 0.148$ and $\chi^2/\text{ndf} = 38.5/29$. The cell size is normalized to 1 and ranges from -0.5 to 0.5.