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Light nuclei identification capability of the PAMELA apparatus

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Abstract: The PAMELA (Payload for Antimatter Matter Exploration and Light nuclei Astrophysics) experiment is a satellite-borne apparatus mounted on the Resurs DK1 Russian satellite, launched from the Baikonur cosmodrome on June 15th 2006. It is designed to study charged particles in the cosmic radiation with a particular focus on antiparticles and light nuclei. The PAMELA apparatus comprises a time-of-flight system, a magnetic spectrometer, a silicon-tungsten electromagnetic calorimeter, an anticoincidence system, a shower tail catcher scintillator and a neutron detector. In this paper the capability of the sub-detectors to identify light nuclei, determinate during the first months of flight, will be presented.

Introduction

The PAMELA experiment [1] is a space-borne apparatus devoted to the study of cosmic rays, with an emphasis on the measurement of the cosmic-ray antiproton and positron energy spectra. The instrument was launched, by means of a Russian Soyuz-TM rocket, on the 15th of June 2006 from the cosmodrome of Baykonur, in the former Soviet Republic of Kazakhstan. It is carried as a "piggy-back" on board of the Russian Resurs-DK1 satellite for Earth observation. The satellite flies on a quasi-polar (inclination 70°), elliptical orbit (altitude 350-600 km), and the expected mission length is of 3 years.

The instrument will measure the spectra of cosmic rays (protons, electrons, and corresponding antiparticles) over an energy range and with a statistics unreachable by balloon-borne experiments. Additionally, PAMELA will search for antimatter in the cosmic radiation, it will investigate phenomena connected with Solar and Earth physics and will measure the light nuclear component of Galactic cosmic rays in the interval 100 MeV/n -200 GeV/n. [1]

The relative abundances of the constituents of Galactic cosmic rays provide information about cosmic-ray transport within the Galaxy. The ratios of the spallogenic nuclei (B, Be, and Li) to mostly primary nuclei such as C are particularly impor-

tant in constraining propagation models since these ratios are sensitive to the amount of material traversed by GCRs from the source to detection at Earth. In addition, abundance ratios tend to be less sensitive to instrumental uncertainties than absolute intensities.

To clarify the role of the different mechanisms that act in the propagation of Galactic cosmic rays it is fundamental to have more precise and extended data on the secondary/primary abundance ratios (like the ratio B/C) and on the fluxes of primary particles: in this field PAMELA can represent a big step ahead.

Object of this paper is the presentation of the light-charge identification capabilities of PAMELA, as evaluated during the flight by different sub-detectors.

The PAMELA instrument

The core of the instrument is a permanent magnet spectrometer equipped with a silicon tracker. The tracking system consists of six 300 μm thick silicon sensors segmented into micro-strips on both sides. The mean magnetic field inside the magnet cavity is 0.43 T with a value of 0.48 T measured at the centre. Momentum is determined for each particle by measuring its deflection in the magnetic field with the silicon detectors.

A sampling electromagnetic calorimeter, composed of W absorber plates and single-sided, macro strip Si detector planes is mounted below the spectrometer. A scintillation shower tail catcher and a neutron detector made of ^{3}He counters enveloped in polyethylene moderator complete the bottom part of the apparatus. The main task of this section is to select positron and antiprotons from like-charged backgrounds.

A Time-of-Flight (ToF) system [4], made of three double-layers of plastic scintillator strips, provides the velocity ($\beta=v/c$) and energy loss (dE/dx) measurements and allows particle identification at low energies.

Particles not cleanly entering the PAMELA acceptance are rejected by the anticoincidence system. The detector is approximately 120 cm high, has a mass of about 470 kg and the power consumption is 355 W.

A very detailed description of the PAMELA detector along with an overview of the entire mission can be found in [2] [3].

Nuclei identification

The PAMELA instruments is optimized for the detection of positrons and antiprotons nevertheless three different sub-detectors (ToF, tracker and calorimeter) are able to identify, with different efficiencies, resolutions and Z ranges, light nuclei. For each detector will be possible to measure the relative abundances of nuclei in different Z ranges. For a more restricted sample of events a highly accurate charge measurement, obtained independently by the three detectors, together with the particle momentum measured by the spectrometer will allow to reconstruct the energy spectrum.

Accurate simulations are in progress to evaluate systematic uncertainties resulting from the various correction factors needed to evaluate fluxes such as uncertainties in the determination of the geometry factor, spallation loss within the instrument, and the tracking efficiency as function of Z.

Nuclei identification with ToF

The data set considered for this study covers the first 9 months of the flight between 2006 June 21 and 2007 April 30.

The data sample was selected by requiring the following cuts:
- single paddle hit on each of the six scintillator layers.
- no signal recorded in anticoincidence system.

The charge of an incident particle is derived from six independent ionization energy loss measurements using the six TOF layers.

The charge calibration of the ToF was performed using samples of relativistic helium selected by the tracker. Once identified, the relativistic helium events were used to obtain the correction factors to normalize the signals of all PMTs, to compensate for variations in gain from PMT to PMT, for gain variations during the flight and to calculate the attenuation lengths of the paddles. By correcting the ADC also for the incident angle of the trajectory of the particle was possible to define the energy release in terms of minimum ionizing particle.

To evaluate the particle charge also in the cases in which the tracking algorithm was not able to reconstruct a track, the same quantity was evaluated by using the spatial coordinates as reconstructed by the ToF. By plotting for each PMT this preliminary (no Time-walk corrections) charge versus β, charge bands for protons and helium were readily observed.

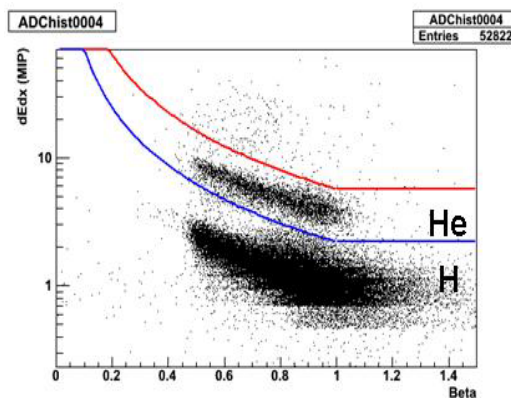From the data set passing the initial cuts, we selected the Z>2 particle candidates by applying a loose dE/dx cut.

Figure 2: The ionization loss in a S12 scintillation counter vs. Beta. The solid curves show the selection criteria for Z=2 and Z >2 particles.

The upper solid curves in Figures 2 show the lower limit used for the selection of Z>2 particles. The region defined by the pair of curves shown in Figures 2 was used to select Z=2 particles as reference sample.

For each scintillator counter we combine the preliminary charge obtained from the two PMT's at the two sides to determine the average charge. The charge bands obtained by applying the aforementioned cut Z>2 for one of the 24 scintillation counters are shown in Figure 3.
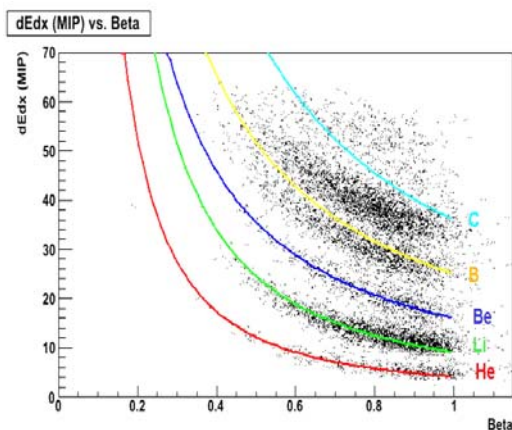

Figure 3: Charge separation obtained with one of the S12 scintillator, illustrated by plotting the ionization energy loss vs. the particle velocity. The solid curves show the theoretical behavior.

A loss of linearity is clearly visible for B and C nuclei. It was already observed in a beam test performed at GSI facility at Darmstadt [5] and is the combined effect of PMTs non linearity, Birks saturation in the scintillator and, for low β C nuclei, front-end electronics saturation.

To correctly combine information of different scintillator layers it is fundamental to exclude from the sample nuclei interacting inside the apparatus. After this selection will be possible to calculate the mean of the energy deposits and fit the bands deriving a charge scale from the results of this fit.

Nuclei identification with Tracker

Ionising energy loss measurements in the six silicon planes of the magnetic spectrometer allow the absolute charge of traversing particles to be determined in independent way.

The signals recorded in the silicon layers of the tracker are grouped in "cluster" structures, where a cluster is defined as one or more adjacent strips with a signal/noise ratio greater than 4 noise sigmas. In figure 4 the ionization loss measured in the tracker versus rigidity are shown.
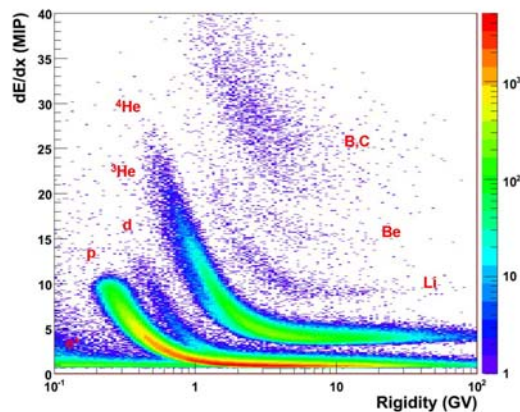

Figure 4: The ionization loss in the tracker vs. rigidity.

The plot is obtained considering the mean of the six measurements. The calibration constant used to convert ADC channels in m.i.p. is the same for all the electronic read-out chips. A more accurate "chip by chip" calibration is in progress and will improve the charge separation. The tracker electronics starts to saturate in correspondence of energy deposit greater than about 16 mips. This loss of linearity for high Z is not surprising since the tracker design was optimized for the detection of relativistic Z=1 particles, focused on the main scientific objectives of PAMELA. The read-out chips have indeed a nominal dynamic range of 10 mips.

Nuclei identification with calorimeter

The charge of the particles can be measured in the calorimeter by considering the energy released in the first plane of the detector which is not covered by tungsten plates. In presence of a reconstructed track, is possible to localize with precision the hit strips and to collect the charge. Figure 5 shows the charge separation obtained with this method.
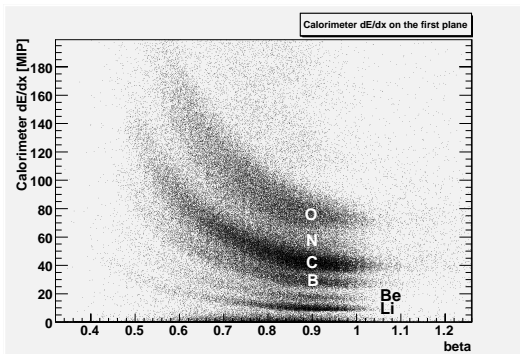
Figure 5: The ionization loss in the first plane of the calorimeter vs. the particle velocity.

More sophisticated methods can be used for nuclei not interacting in the first calorimeter layers. By determining the interaction plane, is possible to use all the multiple energy losses in the planes preceding the interaction to derive the charge of the incident particle.

An iterative algorithm taking into account the energy release along the track as given by the tracking system has been prepared in order to recognize the interaction point inside the calorimeter. Hence a test was performed using the method of the truncated mean to determine the ionization loss in the calorimeter.
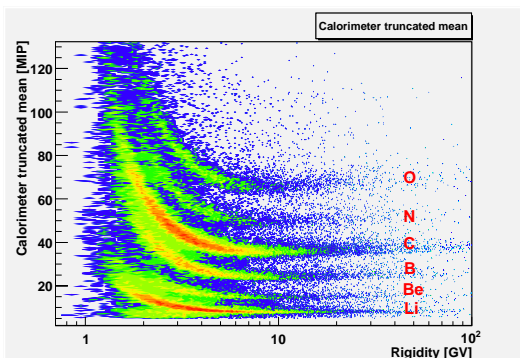

Figure 6: The ionization loss in the calorimeter with truncated mean using three points and at least four dE/dx measurements versus rigidity. A rough cut was used to throw away Helium nuclei which appear as a diffused region at about 2 GV and 5/6 MIP energy release.

We used the three points with the smallest energy measurements to determine the average energy release requiring having at least four dE/dx measurements before the interaction.

Figure 6 shows the charge bands for different nuclei from Lithium to Oxygen obtained with this method. Obviously the charge separation increases with the number of planes required but the efficiency of the measurement decreases.

Another method is under study which consists in the fitting of the energy release on the different planes of the calorimeter as function of the traversed material till the interaction point. This method will also provide an independent energy measurement whenever the nucleus stop inside the calorimeter and the Bragg's peak is visible

Isotope separation

To evaluate the capabilities of PAMELA for mass separation of particles with the same charge, studies have been performed on the separation of proton ($Z = 1$) and helium ($Z = 2$) isotopes. Preliminary results shown that both used methods (β versus rigidity and tracker dE/dx versus rigidity) are promising.

References

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