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Light Nuclei and Isotope Abundance in Cosmic Rays Measured by the Space Experiment PAMELA: Preliminary Results

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Abstract

PAMELA is a space telescope orbiting around the Earth since June 2006. The scientific objectives addressed by the mission are the measurement of the antiprotons and positrons spectra in cosmic rays, the hunt for anti-nuclei as well as the determination of light nuclei fluxes from hydrogen to oxygen in a wide energy range and with very high statistics. The 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 charge identification capabilities of these devices, together with preliminary results concerning isotope abundance, will be presented.

"Keywords: space experiment, cosmic rays, charged particle identification ;"
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1. Introduction

The PAMELA (Payload for Antimatter Matter Exploration and Light nuclei Astrophysics) apparatus [1] is hosted by a Russian Earth-observation satellite, the Resurs-DK1, that was launched into space by a Soyuz rocket on the 15th of June 2006 from the Baikonur cosmodrome. The orbit is elliptical and semi-polar, with an inclination of 70.0° and an altitude varying between 350 km and 600 km.

The main scientific goal of the experiment is the precise measurement of the cosmic-ray antiprotons and positrons energy spectra in an unprecedented energy range (50 MeV - 270 GeV for positrons and 80 MeV - 190 GeV for antiprotons) and with high statistics. Additionally, PAMELA will search for

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antimatter in the cosmic radiation, will investigate phenomena connected with Solar and Earth physics and will measure the light nuclear component of Galactic cosmic rays. In particular, measurements of cosmic rays of primary origin such as Carbon, Nitrogen and Oxygen or their fragments such as Lithium, Beryllium and Boron may provide information about cosmic-ray transport within the Galaxy. The measured ratio of secondary to primary cosmic rays can be used to compute the mean amount of interstellar matter that cosmic rays have encountered before reaching the Earth, which ultimately provides important constraints on the composition and homogeneity of the ISM in which they propagate [2].

In this field PAMELA, that can measure nuclei component of cosmic radiation in the energy interval 80--200 MeV/n, will represent a big step ahead to clarify the role of the different mechanisms that act in the propagation of Galactic cosmic rays.

2. The PAMELA apparatus

The PAMELA apparatus is composed by the following sub-detectors, arranged as in Figure 1, from top to bottom: a T*ime-of-Flight system* (TOF (S1,S2,S3)), an *anticoincidence system* (CARD, CAT, CAS), a *magnetic spectrometer*, an *electromagnetic imaging calorimeter*, a *shower tail catcher scintillator* (S4) and a *neutron detector*. Particles trigger the experiment either via the main trigger provided by the TOF system, composed by 6 layers of segmented plastic scintillators arranged in three planes, or via additional triggers provided by the calorimeter and S4. The TOF system also measures the absolute value of the particles charge and the flight time crossing its planes. In this way downgoing particles can be separated from upgoing ones.

Particles rigidity is determined by the magnetic spectrometer, consisting of a permanent magnet with mean value of 0.43 T, and a silicon tracking system consisting of six 300 μm thick silicon sensors segmented into micro-strips on both sides. In this way, positively and negatively charged particles can be identified.

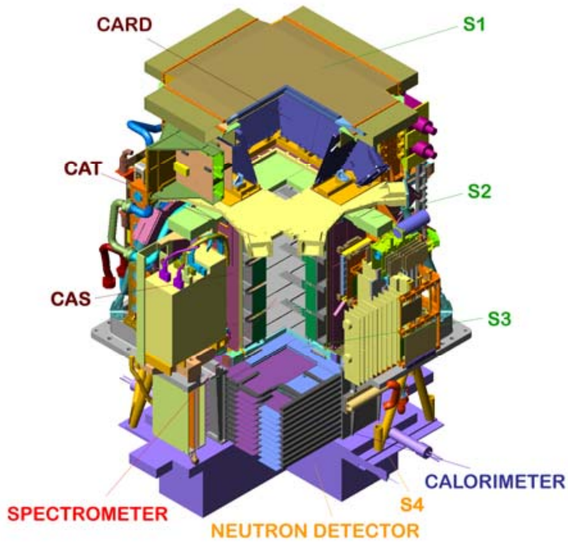

Fig 1. Schematic overview of the PAMELA apparatus. The detector is approximately 1.3 m high, has a mass of 470 kg and an average power consumption of 355 W.

The final identification (i.e. positrons, electrons, antiprotons, etc.) is provided by the combination of the sampling electromagnetic calorimeter, composed of W absorber plates and single-sided macro strip Si detector planes, and the neutron detector information, made of ^{3}He counters enveloped in polyethylene moderator, plus the velocity measurements from the TOF system at low momenta.

A detailed description of the PAMELA detector can be found in [3,4,5].

3. Nuclei Identification

The PAMELA instrument is designed to study charged particles in the cosmic radiation; the three different sub-detectors (ToF, tracker and calorimeter) are able to identify light nuclei with different efficiencies, resolutions and Z ranges. For each detector it 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.

The data set considered for this study covers the first 10 months of the flight between July 2006 and April 2007.

3.1. Nuclei identification with the Tof

The TOF data sample was selected by requiring single paddle hit on each of the six scintillator layers, and no signal recorded in anticoincidence system.

From the data set passing the initial cuts, we selected the Z>1 particle candidates by applying a loose *dE/dx* cut. 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>1 for one of the 24 scintillation counters are shown in Figure 2.

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 variations in gain from PMT to PMT, for gain variations during the flight and to calculate the attenuation length of the paddles. By correcting the ADC also for the incident angle of particle trajectory was possible to define the energy release in terms of minimum ionizing particle.

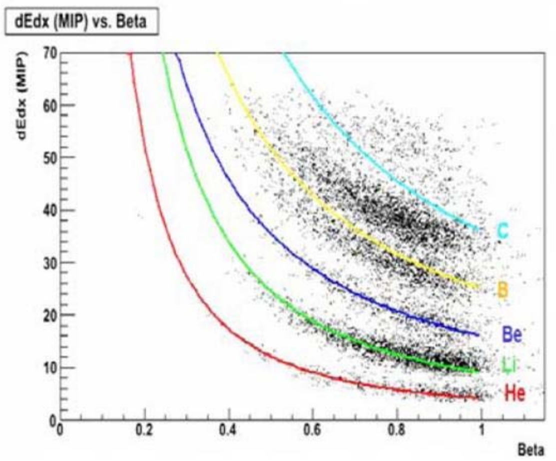

Fig. 2: Charge separation obtained with one of the S12 scintillators, illustrated by plotting the ionization energy loss vs. the particle velocity. The solid curves show the theoretical behavior.

The loss of linearity for B and C nuclei (Figure 2) was already observed in a beam test performed at GSI facility at Darmstadt [6]; this is the combined effect of PMTs non linearity, Birks saturation in the scintillator and, for low β nuclei, front-end electronics saturation.

3.2. Nuclei identification with the Spectrometer

Ionization energy loss measurements in the six silicon planes of the magnetic spectrometer allow the absolute charge of traversing particles to be determined in an 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. In Figure 3 the ionization loss measured in the tracker versus rigidity is shown.

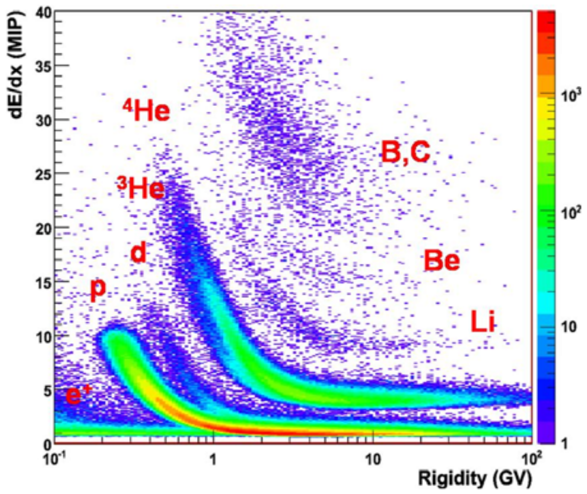

Fig. 3: The ionization loss in the tracker vs. rigidity.

The plot is obtained considering the mean of the six measurements. The calibration constant used to convert ADC channels in mip 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.

3.3. Nuclei identification with the Calorimeter

In the calorimeter the particles charge can be measured by considering the energy released in one, or more than one, plane of the detector. In presence of a reconstructed track, it is possible to localize with accuracy the hit strips and to collect the charge. Figure 4 shows the charge separation bands for different nuclei from Lithium to Oxygen obtained applying this method to the first plane of the detector which is not covered by tungsten plates.

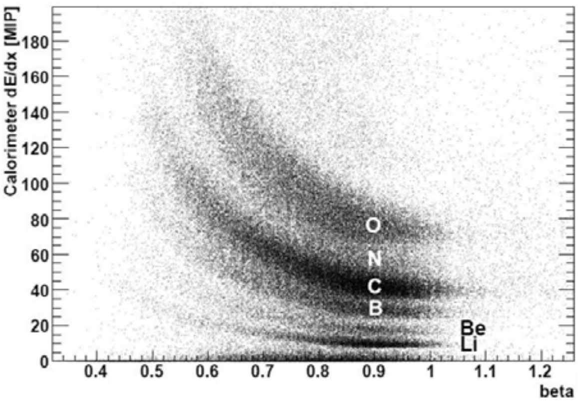

Fig 4: The ionization loss in the first plane of the calorimeter vs. the particle velocity.

Obviously, charge separation increases with the number of planes required but the efficiency of the measurement decreases. In Figure 5 we used the three points with the smallest energy measurements requiring to have at least four *dE/dx* measurements before the interaction.

For nuclei interacting in the deeper layers of the calorimeter more sophisticated methods could be used. By determining the interaction plane, it is possible to use all the multiple energy losses in the planes preceding the interaction to derive the charge of the incident particle. This method will also provide an independent energy measurement whenever the nucleus stop inside the calorimeter and the Bragg's peak is visible.

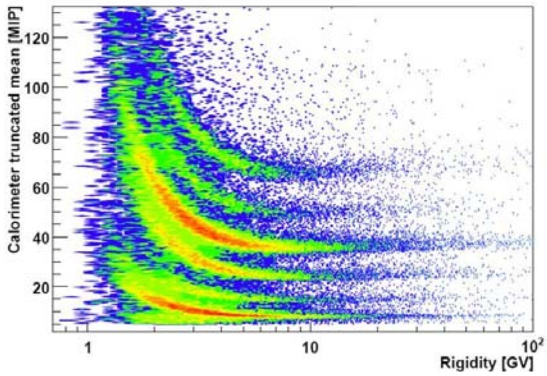

Fig 5: The ionization loss in the calorimeter with truncated mean using three points and at least four *dE/dx* measurements versus rigidity.

4. Isotope separation

To evaluate the capabilities of PAMELA for mass separation of particles with the same charge, studies on the separation of proton (Z = 1) and helium (Z = 2) isotope have been performed. Preliminary results shown that the method β versus rigidity is promising (Figure 6).

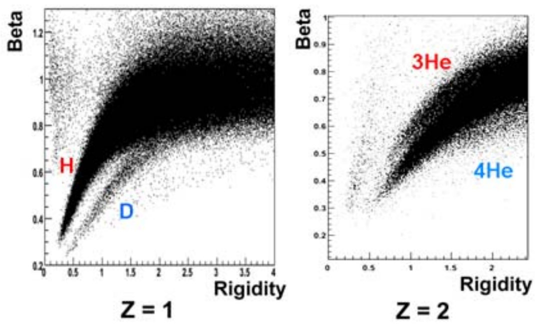

Fig 6: Mass separation for Z=1 and Z=2 particles with the β vs. rigidity method.

5. Conclusions

The preliminary analysis shown in this paper and concerning the light nuclear component of Galactic cosmic rays demonstrate that the PAMELA Tracker, ToF and Calorimeter are able to discriminate light-charged particles. The tracker has an excellent charge discrimination for particles up to Helium, but beyond its performance degrades due to electronic saturation. The ToF can evaluate the particle charge also in the cases in which the tracking algorithm was not able to reconstruct a track. The calorimeter has instead good charge resolution at least up to Z=8.

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