Charge identification in the PAMELA experiment: Preliminary measurements of the B/C ratio

Giuseppe Osteria for the PAMELA Collaboration*

**Istituto Nazionale di Fisica Nucleare, Sezione di Naples, Via Cintia I-80126 Naples Italy.*

***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, in orbit around the Earth since June 15th 2006. The apparatus is able to identify charge particles in the cosmic radiation, in the energy range E $\sim 10^7 \div 10^{12}$ eV by using an array of detectors which includes a time-of-flight system, a magnetic spectrometer, a silicon-tungsten electromagnetic calorimeter. The identification of the charge Z of the incoming particle in the apparatus is performed independently by the three detectors. The tracker system provides good charge resolution for the protons and helium but only a partial resolution for heavier nuclei. A better charge resolution for nuclei (up to Carbon) can be obtained by the ToF system and, also for heavier nuclei, by the first layers of the calorimeter. Preliminary results on flux ratios of nuclei B/C that were obtained by using time of flight system as main charge detector are presented.**

***Keywords*: satellite, cosmic rays propagation, light nuclei.**

I. Introduction

The PAMELA experiment 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 from the cosmodrome of Baykonur, on June 15^{th}, 2006. It is carried as a 'piggy-back' on board the Russian Resurs-DK1 satellite for Earth observation. The satellite flies into a 70.0° elliptical orbit at an altitude varying between 350 km and 610 km. The apparatus is able to identify charge particles in the cosmic radiation, in the energy range E $\sim 10^7 \div 10^{12}$ eV by using an array of detectors which includes a time-of-flight system, a magnetic spectrometer, a silicon-tungsten electromagnetic calorimeter. The instrument measures the spectra of cosmic rays (protons, electrons, and corresponding antiparticles) over an energy range and with a statistics unreachable by balloon-borne experiments. The antiproton-to proton flux ratio and the positron fraction in the energy range 1 $\sim$ 100 GeV have been presented in recent publications [1] [2]. 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 E $\sim$ 100 MeV/n $\div$ 200 GeV/n. 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 important 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.

Object of this paper is the description of the work in progress on the measurement of the ratio boron to carbon with the PAMELA instrument by using the TOF system as main charge detector.

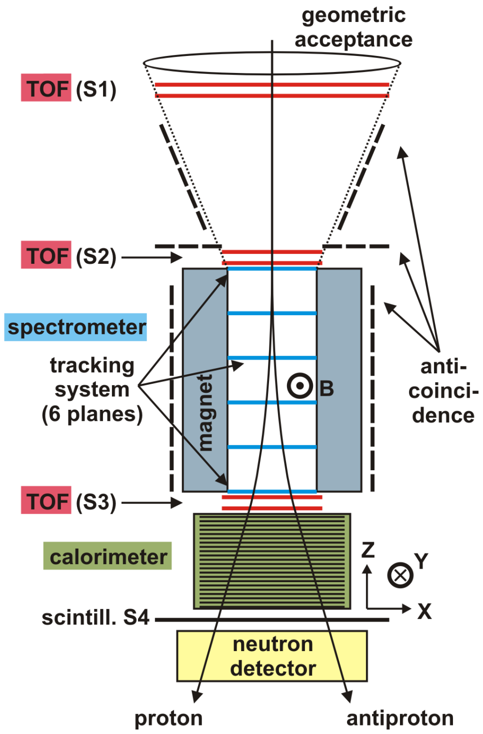


Fig. 1: A sketch of the PAMELA instrument

II. PAMELA INSTRUMENT

As shown in fig. 1, 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 3He 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 [3], made of three double-layers of plastic scintillator strips, provides the velocity (β = 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 [4].

III. CHARGE IDENTIFICATION

A particle traversing the PAMELA apparatus crosses, in the standard trigger configuration, six layers of plastic scintillators, six silicon tracker layers and, at least, the first silicon plane of the calorimeter. For each plane crossed, the ionization energy losses of the traversing particle is measured and recorded by the front end electronics of the three detectors. For particles which do not fragment in the detectors above the first plane of the calorimeter, 13 independent measures of the energy loss are performed. Combining the ionization energy losses measured in these layers with the trajectory defined by the spectrometer and the velocity of the particle (measured either by the Tof or by the the spectrometer), the Z of the particle can be evaluated. More precisely it is possible to evaluate three independent value of Z, Z_{trk}, Z_{tof} and Z_{calo} provided by the three independent charge-determining detectors of the PAMELA instrument, Tracker, ToF and Calorimeter.

In each detector, the charge can be defined by using the single layer measurements separately or by considering a combination of layers to improve the charge resolution. In this last case it is fundamental to exclude from the sample particles interacting inside the apparatus. (The total grammage of the detectors stack, from the top plane of the ToF to the first plane of the calorimeter is about 4.6 g/cm^2).
The final charge resolution and the efficiency in selecting nuclei will depend on the algorithm used to evaluate the charge, starting from the layer information, and, eventually, on the combination of subdetectors used to define the charge. In the present analysis the Z measured by the tracker, Z_{trk}, is obtained by calculating the simple mean of the charges measured in the layers hit along the track. The Z_{calo} is evaluated by considering the energy released in the first plane of the detector which is not covered by tungsten plates. The combination of layers of the ToF system used to define Z_{tof} will be described in more details in the next section.

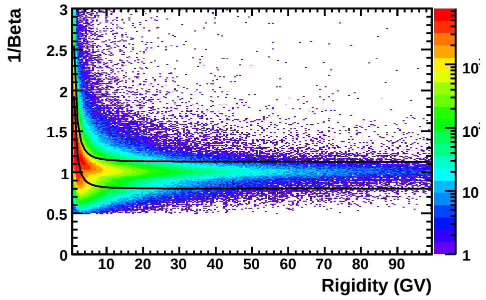
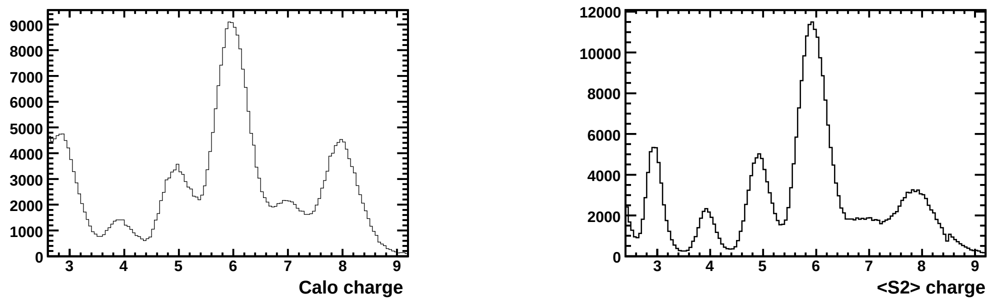


Fig. 2: Consistency condition between the β measured by the ToF system and the rigidity measured by the spectrometer

The redundancy of information offered by the three subdetectors is partially reduced as the charge of the crossing particles increase. The tracker and the ToF systems are indeed optimized for Z=1 particles and lose linearity for high Z particle. In particular the small dynamics of the front end chips of the tracker allows for a good charge separation only in the range from Z = 1 to about Z = 4.
The dynamic range of the TOF, covers nuclei from Z = 1 to Z = 6 in the whole β range, including also relativistic oxygen nuclei (Z = 8). In this case the limitations derive from the impossibility of using the dynode signal of the PMTs, due to the constrain on the total weight and power imposed by the satellite. The calorimeter covers the widest Z range, but the single layer method works fine only if applied to particles recognized as nuclei by other detectors. This simple method produces a lot of heavier 'fake' nuclei if applied to the whole sample of protons and Helium impinging on the apparatus. More sophisticated methods can be used for nuclei not interacting in the first calorimeter layers but will not be used in this analysis. A description of the work in progress on this item is in [5].
The ranges of Z of the three sub detectors ensure the possibility of performing, with PAMELA instrument, a simultaneous measurement of the fluxes of the secondary light nuclei Li, Be and B respect to the flux of the primary C in a very wide range of energy. In this work, the ToF system is used as main charge detector and the Z_{trk} and the Z_{calo} are respectively used to select heavier nuclei in the enormous 'background' of protons and helium and to study the efficiency of the selection cuts.



(a) Calorimeter (b) Mean of S2 layers

Fig. 3: An example of charge spectra obtained with Calorimeter (left panel) and with the S2 plane of the ToF (right panel).

IV. NUCLEI SELECTION

The first step, done in order to perform this analysis, was to developed a specific procedure to track nuclei with Z $>$ 2. The standard tracking algorithm is indeed optimized for protons and shows a decreasing efficiency in reconstructing tracks as the charge of the particle increases. The effect is clearly due to delta-rays produced by nuclei traversing the spectrometer, which increase with the Z of the particle, and produce spurious hits in the silicon layers. The new algorithm has significantly improved the tracking efficiency. The procedure and the improvement in the efficiency will be described in detail elsewhere. [5]

The data considered for this study was acquired in the period July 2006 to December 2008. A set of selection criteria was imposed on the whole data set to preselect nuclei rejecting much more abundant protons and Helium nuclei (Z = 2):

- single reconstructed track in the spectrometer with a good χ^2 for the fitted track.
- A geometrical cut to ensure that particle is inside the acceptance of the apparatus
- Less then three paddles hit on each of the six scintillator layers.
- $\beta > 0$.
- Z_{tof} (layer S11 or layer S12) or Z_{trk} greater the 2.3.

Further selection cuts were imposed to reject event for which the reconstructed rigidity and the measured β are inconsistent as well as events with a reconstructed rigidity exceeding the estimates vertical geomagnetic cut-off by a factor 1.2. Fig. 2 shows the selection operated by the first cut.

After applying the previously described cuts, we obtain a clean sample of nuclei. The condition imposed on β excludes from the sample the contamination from albedo particles (time resolution of about 100 ps over a time-of flight of 3 ns), the condition imposed on the quality of the reconstructed track helps to reject the particles interacting in the instrument (above the S3 plane).

TABLE I: Mean and sigma values for the gaussian fits of the Carbon peak on S2 plane

Energy range(GeV/n)	mean	sigma
0.2-0.4	6.0	2.92 10^{-1}
0.4-0.6	6.0	2.78 10^{-1}
0.6-0.8	6.0	2.75 10^{-1}
0.8-1.0	6.0	2.54 10^{-1}
1.0-2.0	5.9	2.48 10^{-1}
2.0-3.0	5.9	2.46 10^{-1}
3.0-4.0	5.9	2.33 10^{-1}
4.0-6.0	5.9	2.46 10^{-1}
6.0-10.0	5.9	2.46 10^{-1}
10.0-20.0	5.9	2.52 10^{-1}
20.0-50.0	5.9	2.60 10^{-1}
50.0-100.0	5.9	2.66 10^{-1}
100.0-200.0	5.9	2.86 10^{-1}

The charge spectra obtained with the calorimeter and with the ToF plane S2 (average of two layers) for this first selection of events are shown in fig. 3.

Both the charge distributions extends from Lithium to Carbon nuclei and, with lesser efficiency, up to the Oxigen. As explained, the reduced efficiency for oxygen in the ToF system is due to the saturation of the electronics, while, in the Calorimeter, this effect is due to the loss of efficiency of the tracking algorithm for heavier (Z $>$ 6) nuclei (only event with a good reconstructed track are selected).

The strategy selected to process charge data from ToF system for this analysis was to consider the information coming from different layers separately and to impose consistency in the charge assignments between layers. In particular, in each of the ToF layers, a nucleus is classified as having charge Z, if the measured Z coincide, within 1 (1.5) sigma, with the relative charge peak of the layer. In turn, a nucleus is classified as having charge Z_{tof} = Z if at least four layers measure the same Z .

The ToF layers selected to evaluate the charge of the particle,in this first approach, are S_{11}, S_{12} and the mean of the planes S_{21} and S_{22}.

The energy of the nucleus was estimated by using the rigidity measured in the spectrometer as well as, at lower energy, the velocity measured by the ToF. The whole energy range was divided in 12 intervals and, for each interval, a charge spectra similar to right panel of fig. 3 was obtained for each of the six ToF layers. The spectra were decomposed by Gaussian fits and the positions of the peaks and the relative sigmas were determined. In Table I the values relative to the Carbon obtained for the plane S2 for the different energy bins are shown. Similar values are obtained for the majority of the energy bins and nuclear species considered.
These values are in good agrement with charge resolution measured in a light-nuclei beam test performed at GSI beam accelerator. [6]

According to these results, to apply the defined Z classification criteria for a Tof layer, corresponds to place a cut of 0.2 - 0.3 charge units on all the peaks of the charge spectra similar to the one shown in the right panel of fig. 3. By requiring the same condition on the described group of layers a very good separation between charge population is obtained.

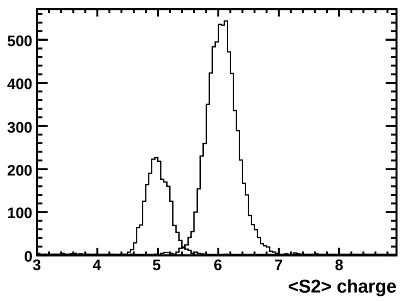


Fig. 4: Charge measured on the ToF plane S2 when the particle is identified as Carbon (Boron) simultaneously on the layers S11 and S12.

Fig. 4 shows, as an example, the charge measured on the S2 plane, for a particular energy interval, when requiring that the charges measured on the layers S11 and S12 is simultaneously that one relative to Carbon (Boron) nuclei.
After the correction for the relative selection efficiency in each energy bin, the ratios between nuclear species are evaluated.

In the whole considered energy range, the total number of nuclei of different species, selected according the described procedure, are reported in Table II. At this stage the corrections for the energy spill-over between the bins due to instrumental resolution are not yet taken into account. The study of the efficiency of the whole set of selection criteria included an estimates of the tracking efficiency is described in detail in [5].

TABLE II: Number of identified nuclei before efficiency correction

Nucleus	Number of events
Li	$\sim 2.5\ 10^4$
Be	$\sim 1.2\ 10^4$
B	$\sim 4.0\ 10^4$
C	$\sim 1.2\ 10^5$
O	$\sim 4.2\ 10^4$

The contamination due to the misidentification between charges has been evaluated and is less than 1% for B and C nuclei.
Accurate simulations are still 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 efficiency as function of Z.

V. Discussion

The results on the measured ratio of B/C will be show, at the status of art, during the conference.

The described approach, as already underlined, has to be considered as just one of the possible strategies to analize charge data from our instrument. Also limiting the choice to approaches which use the ToF system as main charge detector, several other strategies exist. The chosen approach ensures a good background rejection capability, allows for an easy evaluation of the efficiency, but surely does not maximize the statistics. Moreover, in this method, the S3 plane is not used to measure the Z of the particle but only to evaluate the efficiency of the selection cuts. This choice is due to fact that this plane is exposed to back-scattered particles produced by nuclei interacting in the calorimeter which could alterate the charge measurement. However, with the due care, the charge measurement of S3 plane can help in further reducing the number of interacting events in the spectrometer and consequently the background.
Work is progress on comparing the results obtained with different choice of Tof layers used to define the charge from which the final charge resolution, the statistics and the background will depend.

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