PAMELA MISSION:
preliminary results about nuclei analysis

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***Abstract*— The PAMELA (Payload for Antimatter Matter Exploration and Light nuclei Astrophysics) experiment is a satellite-borne apparatus that will make long duration measurements of the cosmic radiation over an extended energy range with a particular focus on antiparticles and light nuclei. Specifically, PAMELA will measure the cosmic-ray antiproton and positron spectra over the largest energy range ever achieved and will search for antinuclei with unprecedented sensitivity. Furthermore, it will measure the light nuclear component of cosmic rays and test cosmic-ray propagation models.**

PAMELA is housed on-board the Russian Resurs-DK1 satellite, which was launched from the Baikonur cosmodrome on June 15th 2006 in an elliptical (350-610 km of altitude) orbit with an inclination of 70 degrees. PAMELA consists of: a permanent magnet spectrometer which provide rigidity and charge sign information; a Time-of-Flight and trigger system for velocity and charge determination; an electromagnetic imaging calorimeter for lepton/hadron discrimination; a shower tail catcher scintillator and a neutron detector. An anticoincidence system is used offline to reject false triggers.

This paper reviews the capability of the PAMELA subdetectors to identify light nuclei; preliminary results about nuclear abundance ratios will be presented.

I. THE PAMELA INSTRUMENT

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 a Russian Soyuz-TM rocket on the 15th of June 2006 from the cosmodrome of Baykonur in 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 350-610 km), and the expected mission length is 3 years.

The instrument measures the spectra of cosmic rays (protons, electrons, and corresponding antiparticles) over a wide energy range and with a statistics unreachable by balloon-borne experiments. Additionally, PAMELA is searching for antimatter in the cosmic radiation and it is investigating phenomena connected with Solar and Earth physics and measuring the light nuclear component of Galactic cosmic rays in the interval 100 MeV/n - 200 GeV/n.

The apparatus is $\sim$ 1.3 m high, has a mass of 470 kg and an average power consumption of 355 W.

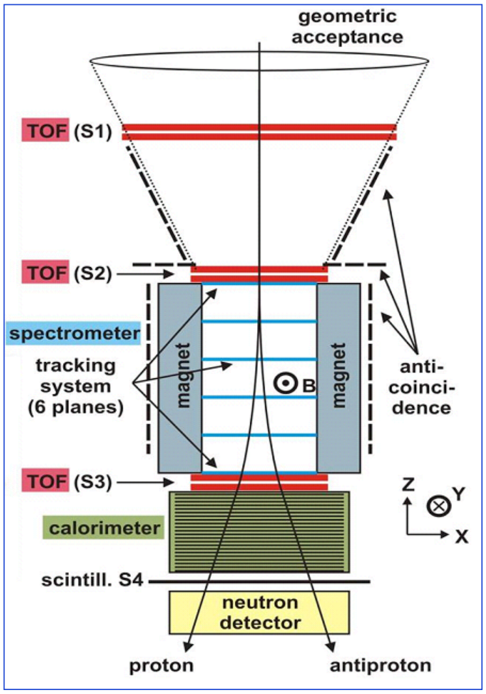

Fig. 1. PAMELA apparatus with its reference system.

The PAMELA apparatus is composed of the following subdetectors, arranged as shown in figure 1:

- a Time of Flight system (ToF: S1, S2, S3);
- a magnetic spectrometer;
- an anticoincidence system (CARD, CAT, CAS);
- an electromagnetic imaging calorimeter;
- a shower tail catcher scintillator (S4);
- a neutron detector.

PAMELA is built around a 0.43 T permanent magnet spectrometer equipped with 6 planes of double-sided silicon detectors allowing the sign, absolute value of charge and momentum of traversing charged particles to be determined. The acceptance of the spectrometer (which also defines the overall acceptance of the PAMELA experiment) is 21.5 cm^2s and the maximum detectable rigidity is $\sim$ 1 TV. Spillover effects limit the upper detectable antiparticle momentum to $\sim$ 190 GeV/c ($\sim$ 270 GeV/c) for antiprotons (positrons). The spectrometer is surrounded by a plastic scintillator veto shield.

An electromagnetic calorimeter, mounted below the spectrometer, measures the energy of incident electrons and allows topological discrimination between electromagnetic and hadronic showers (or non-interacting particles). Planes of

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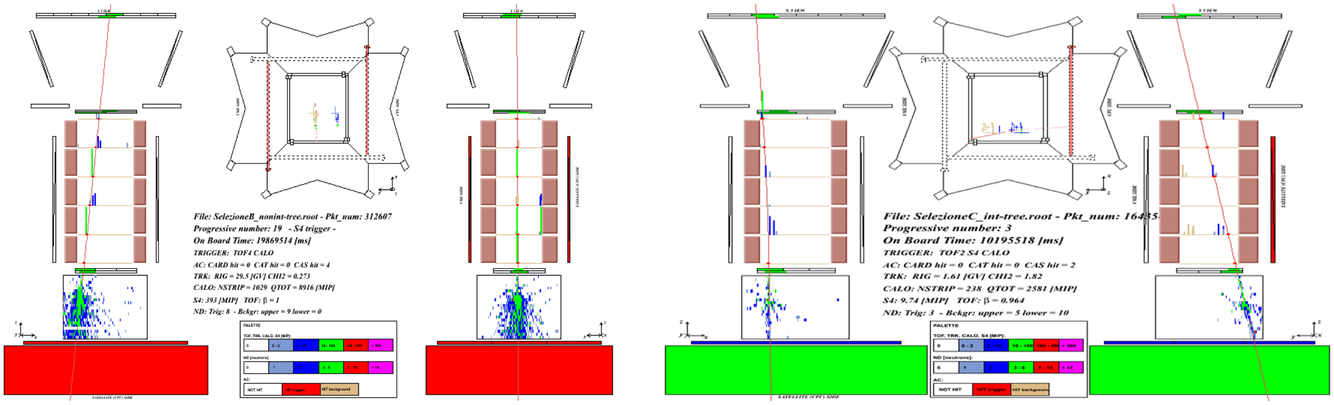

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(a)

(b)

Fig. 2. Boron (a) and Carbon (b) as detected by the PAMELA instrument.

plastic scintillator mounted above and below the spectrometer form a Time of Flight (ToF) system which also provides the primary experimental trigger. The timing resolution of the ToF system allows albedo particles to be identified and proton-electron separation to be performed below $\sim$ 1 GeV/c. Ionising energy loss measurements in the Time of Flight scintillator planes and in the silicon planes of the tracking system allow the absolute charge of traversing particles to be determined.

The volume between the upper two ToF planes is bounded by an additional plastic scintillator anticoincidence system. A plastic scintillator system mounted beneath the calorimeter aids in the identification of high energy electrons and is followed by a neutron detection system for the selection of very high energy electrons (up to 2 TeV) which shower in the calorimeter but do not necessarily pass through the spectrometer.

In figure 2, two nuclear events (Boron and Carbon respectively) detected by PAMELA instrument are shown. The hadronic interactions inside the calorimeter are clearly visible, as well as the activity recorded by the neutron detector.

II. THEORETICAL IMPORTANCE OF BORON TO CARBON RATIO

Most of the available information about matter in our Universe, and in our Galaxy in particular, comes indirectly from the detection of the electromagnetic radiation (from meter waves to γ rays) that is emitted or absorbed by this matter. A completely different information is provided by the cosmic ray nuclei, which constitute a genuine sample of galactic matter. Many different nuclei species are observed, in a wide range of energy, and with different origins.

The sources of CR are believed to be supernovae (SNe) and supernova remnants (SNRs), pulsars, compact objects in close binary systems, and stellar winds. Observations of X-ray and γ-ray emission from these objects reveal the presence of energetic particles thus testifying the efficient acceleration processes in their neighborhood [2][3]. Particles accelerated near the sources propagate tens of million years in the ISM before escaping into the intergalactic space. In the course of CR propagation secondary particles and γ-rays are produced, and the initial spectra and composition of CR species change. The destruction of primary nuclei via spallation gives rise to secondary nuclei and isotopes (rare in nature), antiprotons and pions ($\pi^{\pm}$, π^{0}) that decay producing secondary $e^{\pm}$'s and $\gamma-$rays. The CR source composition and CR propagation history are imprinted in their abundances.

The relative abundances of the constituents of Galactic cosmic rays provide information about cosmic-ray transport within the Galaxy. In particular, cosmic rays of primary origin such as Carbon and Oxygen may interact with the interstellar medium to produce secondary fragments such as Lithium, Beryllium and Boron. 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.

One of the most sensitive quantity is B/C, as B is purely secondary and its main progenitors C and O are primaries. The shape of this ratio is seriously modified by changes in the propagation coefficients. Measuring the energy dependence of the B/C ratio we can infer the diffusion coefficient $D(E)$, or more in general the escape time as a function of energy, which scales as $1/D(E)$ if diffusion is the only process responsible for escape. Moreover, B/C ratio is also the quantity measured with the best accuracy, so that it is ideal to test models. Indeed, as a ratio of two nuclei with similar Z, it is less sensitive to systematic errors and to Solar modulation than single fluxes or other ratios of nuclei with more distant charges. For the same reasons, the sub-Fe/Fe may also be useful. Unfortunately, since existing data are still affected by sizeable experimental errors, we can only use them to cross-check the validity of B/C but not to further constrain the parameters under scrutiny. It is important to recall that existing experimental results at energies smaller than $\approx$ 30 GeV/n suggest that the diffusion coefficient scales with energy as $D(E) \propto E^{\delta}$, with $\delta \approx$ 0.6, at least at rigidities below $\sim$10 GV. The variable δ is the key parameter in the description of cosmic-ray diffusion from the Galaxy.

A better determination of the cosmic ray propagation is fundamental for the search of exotic matter, like dark matter candidates or antimatter produced in exotic processes, since the signature of such processes can be recognized only by knowing with great precision the fluxes due to the conventional production, acceleration and transport models [4][5][6].

III. Boron to Carbon ratio with the PAMELA Experiment

In the energy range between 200 MeV/n and 3 GeV/n the best accurate estimation of the B/C ratio with the Pamela instrument has been obtained using only Calorimeter and TOF information. In figure 3 a 2-D histogram of the energy released in the first layer of the Calorimeter versus the 'beta' (ratio between the particle velocity and the speed of light) value for each nuclear event is shown. Different families are identifiable up to Oxygen, with the exception of Nitrogen due to its low statistic. Starting from this result, it is possible to identify each nuclear family and fit it by an exponential function. Using as reference the fitted curves, a simple interpolation method allows Z reconstruction for all events.

To obtain a better resolution, the result could be improved by using more Calorimeter planes for the estimation of the energy released for each event, but to the detriment of the precision of the ratio, due to the different interaction cross sections with tungsten for Boron and Carbon nuclei. To obtain a better discrimination between different families, the energy range between 200 MeV/n and 3 GeV/n has been divided into six energetic bins.

Starting from Z reconstruction histograms relative to different energy bins, it is quite simple to obtain the Boron to Carbon ratio. We made a triple gaussian fit correlating in this way Beryllium, Boron and Carbon behaviors (as shown in figure 5, upper, for the energy interval 0.2 - 0.4 GeV/n) and then we used the parameters obtained by this triple fit to do single fits on Boron and Carbon peaks (bottom). B/C values have been achieved as the ratio between the two subtended relating areas, as shown in the bottom part of figure 5. It is important to underline that these values have to be corrected for the different Tracker efficiency in reconstructing Boron and Carbon nuclei tracks, and for the different Calorimeter efficiency in the detection of the same particles.

IV. Efficiency estimation

A. Tracking reconstruction efficiency

At this phase of the analysis the PAMELA tracking reconstruction software routine is optimized for tracking Z=1 particles; it is not complete for the nuclei events.

To estimate the tracking reconstruction efficiency as a function of the particle energy, a Boron and a Carbon confident sample has been selected from Calorimeter and TOF. Then, the track efficency has been obtained at low energy imposing only single track existence.

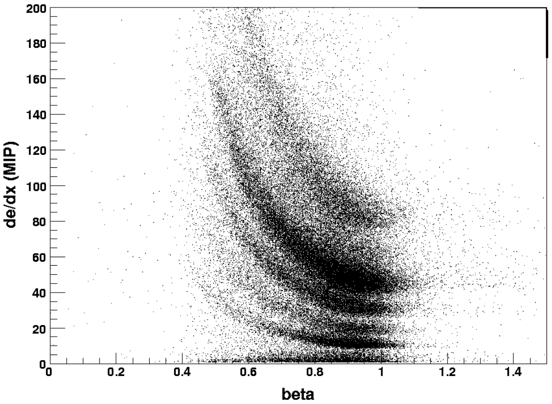

Fig. 3. Nuclear families: energy released in Calorimeter first plane versus beta value. Particles fall into distinct charge bands.

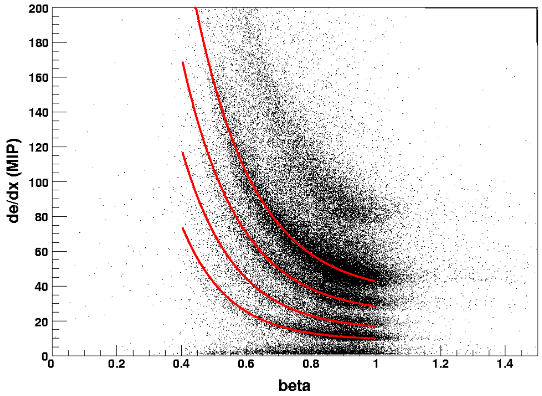

Fig. 4. Nuclear families: energy released in Calorimeter first plane versus beta value. Particles fall into distinct charge bands. Fit is superimposed for each family.

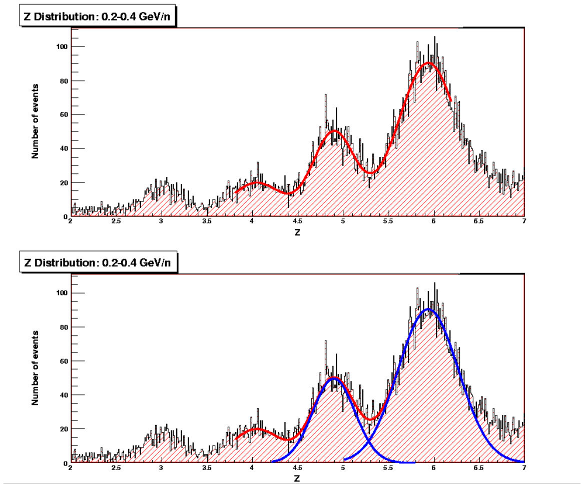

Fig. 5. Z reconstruction for events with energy in the interval 200 MeV/n - 400 MeV/n. Upper: Triple gaussian fit to correlate Berillium, Boron and Carbon families is superimposed. Bottom: Single gaussian fits for Boron and Carbon peaks are superimposed.

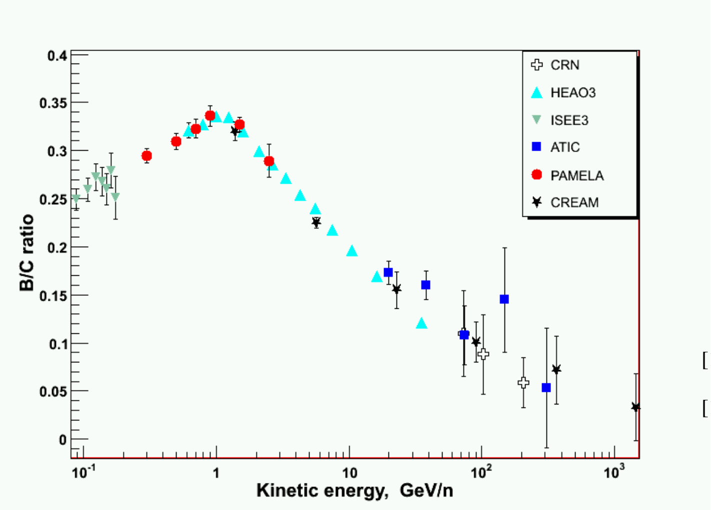

Fig. 6. Preliminary Boron to Carbon ratio measured by PAMELA. Results from other experiments are also shown: ATIC [7], HEAO3 [8], CREAM [9], ISEE3 [10], CRN [11].

B. *Calorimeter Efficiency*

The percentage of Boron and Carbon events triggered by PAMELA apparatus but not detected by the Calorimeter, as a function of the particle energy, is not the same. For this reason is important to calculate the Calorimeter efficiency for a correct B/C ratio estimation.

A confident sample of Boron and Carbon nuclei has been obtained using TOF System. Then, the number of nuclei releasing energy along the reconstructed track in the first layer of the calorimeter is considered. The efficiency, calculated for the same energy bins used for B/C ratio calculation, is given by the ratio between this number and the primary sample.

V. PRELIMINARY RESULTS

B/C ratio has been calculated with the Pamela experiment taking into account the Tracker and Calorimeter efficiencies. PAMELA results are shown in figure 6 together with the main experimental data existing in literature. PAMELA data seem to be in good agreement with other experimental data. It is important to notice that PAMELA results partially cover an unexplored region (200 MeV/n - 600 MeV/n) and that it is the only experiment, besides HEAO3, that reproduces the peak at $\sim$ 1 GeV/n, confirming previous results.

In conclusion, this is only a first analysis of the nuclear components of cosmic rays detected by the PAMELA instruments. This work is in progress.

More statistics needs to be added, and a better tracking algorithm will allow to recover events discarded in this analysis. Neverthless the data obtained in the first analysis seem to be promizing. Furthermore, the statistics will be greatly improved in the next future.

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