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In-orbit performances of the magnetic spectrometer of PAMELA

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Abstract: PAMELA cosmic-ray detector is orbiting around the Earth on board the Resurs DK1 satellite since June 2006. The experiment is designed to study charged particles in the cosmic radiation, being optimized in particular for antiprotons and positrons. The core of the detector is a spectrometer composed of six planes of silicon microstrip sensors, which are placed inside the magnetic cavity of a permanent magnet. The apparatus is used to reconstruct the trajectory of cosmic rays which cross the cavity, and to measure their momentum and charge. In this paper the main features of the spectrometer are reviewed and its performances in flight are shown.

Introduction

PAMELA (*Payload for Antimatter/Matter Exploration and Light-nuclei Astrophysics*[1]) is a satellite-borne experiment which has been designed to study charged cosmic rays, in particular having been optimized to reveal the rare antiparticle component of the cosmic radiation [2]. Its principal aim is the measurement of the energy spectra of antiprotons and positrons with high precision and over a wide range, but also other more common components like protons, electrons and light nuclei will be thoroughly investigated. This will allow to look for evidences of the existence of dark matter, to check the correctness of cosmic-ray propagation models and also to test for the possible presence of antinuclei by direct detection.

Beside momentum measurement, particle identification is performed with the help of the other detectors included in the PAMELA apparatus [3] (see figure 1): a three-plane time-of-flight system, an electromagnetic imaging silicon-tungsten calorimeter, an anticoincidence system around and on top of the magnet, a shower-tail catcher scintillator under the calorimeter (S4) and a ^{3}He neutron detector.

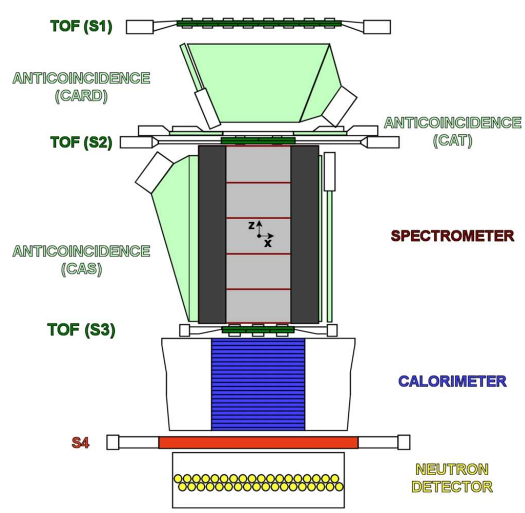

Figure 1: Schematic drawing of the PAMELA detector. The height of the apparatus is approximately 1.3 m.

The magnetic spectrometer

The central components of PAMELA are a permanent magnet and a tracking system composed of six planes of silicon sensors, which form a magnetic spectrometer [4]. This device is used to determine the rigidity $R = pc/Ze$ and the charge of particles crossing the magnetic cavity. The design had to take into account the strong limits imposed by a satellite mission as regards mass, volume, power and the amount of data to be transmitted to ground. The rigidity measurement is done through the reconstruction of the trajectory based on the impact points on the tracking planes and the resulting determination of the curvature due to the Lorentz force. The direction of bending of the particle (i.e. the discrimination of the charge sign) is the key method used to separate matter from antimatter.

The magnetic field of the spectrometer of PAMELA is generated by a permanent magnet composed of five identical modules put one on top of another to form a tower which is 43.6 cm high. The detecting planes of the tracking system are housed in slits, located between each couple of modules, as well as at the top and at the bottom of the structure. The modules contain blocks of a sintered Nd-Fe-B alloy (residual induction $\simeq 1.3$ T) glued together and have a longitudinal cavity that measures 13.1 cm × 16.1 cm. The resulting B field in the spectrometer is almost uniform both in module (average value $B \simeq 0.43$ T) and in direction (the field points along the negative direction chosen as the Y axis of the reference frame of PAMELA, while the Z axis is directed along the cavity and the X axis is obtained as a consequence in order to get a set of right-handed coordinates. See figure 1). Since the prevalent direction of motion of cosmic-ray particles is along Z, the Lorentz force causes their trajectory to curve mostly in the X direction, so that the bending plane is identified by the X and Z axes. Ferromagnetic screens are placed on the sides of the tower, and they ensure that the external stray field is lower than the limit required for the safe working of the satellite, and for the correct functioning of the other devices of PAMELA (in particular of the photomultipliers used to detect the light output of the scintillators).

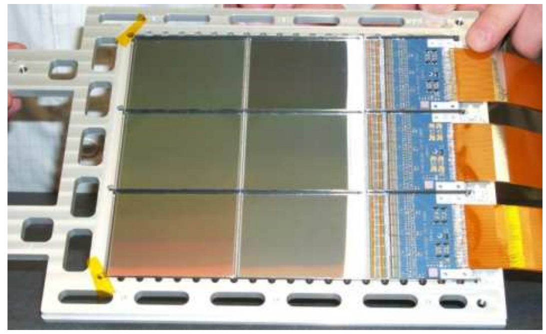

Figure 2: A plane of the tracking system, composed of six silicon sensors and their front-end electronics.

One of the detecting planes of the tracking system is shown in figure 2. Each plane contains three independent elementary parts, called *ladders*, glued together side by side and fastened within an aluminium frame. The *ladder* is the basic detecting unit of PAMELA's tracker, and it is composed by a couple of silicon sensors and by an Al_2O_3 *hybrid circuit* which contains the front-end electronics. Each sensor has a surface of 5.33 × 7.00 cm and is 300 μm thick. Four thin carbon-fiber bars glued at the sides of the *ladders* are used to strengthen the mechanical structure of the plane, and they also provide the binding points of the sensors to the frame. This detector set-up allows to place the detecting planes inside the magnetic field of the spectrometer without any additional structure to support them: the *ladders* are attached to the magnet just by their edges and they stay hanging inside the cavity, thus minimizing the amount of matter which particles have to cross on their path. In this way the ionization energy loss of particles is kept low and the multiple scattering, which is the main cause of the momentum resolution worsening at low energies, is reduced. This mechanical configuration has been carefully designed and it has successfully withstood the stresses due to the launch of the satellite and the orbital maneuvers. The silicon microstrip sensors are double sided, and they can measure both the orthogonal coordinates of the charged particles which cross them. Strips are implanted with a pitch of 25.5 μm on the *junction side* (read-out pitch 51 μm) which is used to mea-

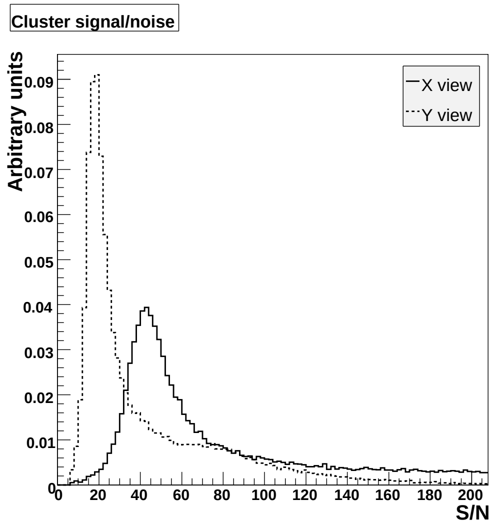

Figure 3: Distribution of the signal/noise ratio for clusters on the X and Y sides of one plane.

sure the coordinate along the bending direction, and 66.5 μm on the *ohmic side*.

As front-end electronics, 8 128-channel VA1 chips are used for each *ladder*. The low noise and low power consumption which characterize these chips allow the detector to get a high spatial resolution and to comply with strict power requirements of the satellite.

Overview of the performances of the magnetic spectrometer

The in-flight calibration of PAMELA is currently underway, and the results show that the detectors are working as expected and fulfill the nominal requirements. Some preliminary studies about the spectrometer's performances in orbit are here reviewed: significant improvement can be expected once the calibration is completed.

The rigidity resolution of the spectrometer depends (besides the number of measurements along the track, their distance, and the magnetic field intensity) on the contribution due to multiple scattering at low energies, and on the position measurement error along the bending direction (X) at high energies. In turn, the impact point resolution is related to the signal/noise ratio which can be achieved in detecting the clusters of charge which are released by the ionizing particles when crossing the silicon sensors. The distribution of the signal/noise ratio for clusters on one of the planes of the tracking system is shown in figure 3. The signal/noise ratio for a cluster is defined as the sum of the signal/noise ratios of the strips which collect the ionization charge. The mean values are consistent with those obtained during beam test sessions, $\simeq 56$ for the X side and $\simeq 26$ for the Y side. This leads to spatial resolutions for orthogonally incident particles of about 3.0 μm and 11.5 μm respectively. Results of test with proton beams show that the upper value of the rigidity for which the relative error equals 1 (the so-called Maximum Detectable Rigidity or MDR) is $\simeq 1$ TeV.

Data acquired at beam tests have been used also to develop and apply a software procedure which allows to take into account the real positions of the silicon sensors, which have to be known very accurately if such a high spatial resolution is not to be wasted. This alignment procedure has been later combined and checked by means of cosmic rays detected by PAMELA on ground before the launch, and it will be completed by a similar procedure which exploits cosmic protons and high-energy electrons during the flight.

The measured spectra of hydrogen and helium (in arbitrary units), as a function of the kinetic energy per nucleon is shown in Figure 4. Spectra have been corrected to take into account the effect of the geomagnetic cut-off at low energies.

Besides rigidity and charge sign, the tracking system can also be used to determine the absolute value Z of the charge, by multiple measurements of the mean rate of energy loss in the silicon sensors. Figure 5 shows the Z discrimination capability of the tracking system. The task of selecting charge of particles can be accomplished in PAMELA by the time-of-flight system and the calorimeter, too [5]. Nonetheless, the spectrometer can contribute with a good charge resolution at least up to Be (when the single-channel saturation of the silicon sensors reduces the performances), and it is also able to perform isotopic discrimination for H and He at low rigidities.

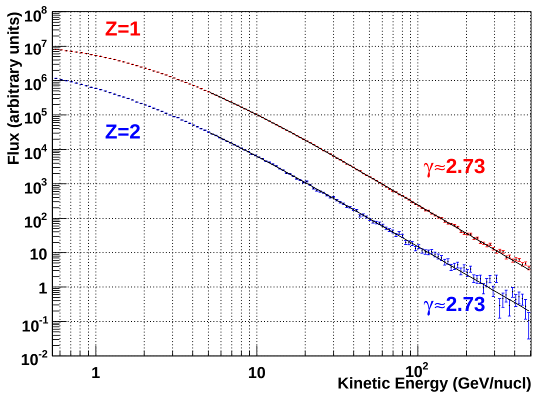

Figure 4: Hydrogen and Helium spectra (corrected for the geomagnetic transmission effect) as a function of the kinetic energy per nucleon. A simple parametrization is superimposed on data, and the corresponding spectral index is shown.

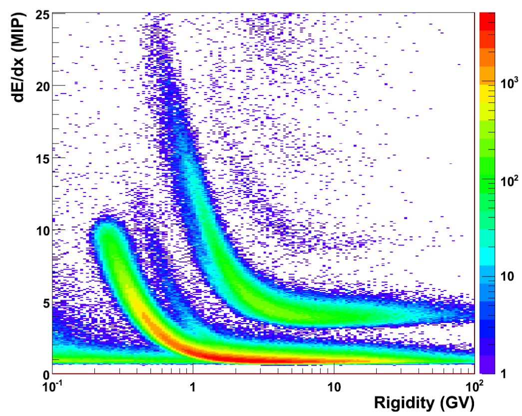

Figure 5: Distribution of the mean rate of energy loss in the silicon sensors of the tracking system, as a function of the particle rigidity, for a sample of positively charged cosmic rays. Moving from bottom-left to top-right, the following particle species can be recognized: e^+, p and d, ^{3}He and ^{4}He, Li, Be, B and C.

Conclusions

The magnetic spectrometer of the PAMELA experiment has been designed and built by the Florence group of the PAMELA collaboration. The flight model of the instrument has been completed in 2001 and several tests on accelerator beams have been performed in order to study its performances.

Since June 2006 the detector have been orbiting around the Earth and it has been taking data for nearly one year. The preliminary analysis of the collected data show that the expected performances fulfill the design requirements needed to investigate the questions about antimatter in cosmic rays.

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