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PAMELA: A payload for antimatter matter exploration and light nuclei astrophysics

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Abstract

PAMELA is a satellite-borne experiment designed to study the charged component of the cosmic radiation, with particular emphasis on antiparticles. PAMELA is mounted on the Resurs DK1 satellite that was launched on June 15th 2006 from the Baikonur cosmodrome and has a foreseen lifetime of at least 3 years. The PAMELA apparatus consists of a magnetic spectrometer, an electromagnetic calorimeter, a time-of-flight system, an anticoincidence system, a shower tail catcher scintillator and a neutron detector. The signal from all detectors allows a reliable identification of antiparticles in a large background of other charged particles. The first studies of the in-flight performance are presented in this article.

1. Introduction

The PAMELA satellite experiment[1] (a Payload for Antimatter–Matter Exploration and Light-nuclei Astrophysics) [1] is designed to study the charged component of the cosmic radiation during the 24th solar minimum, with particular emphasis on antiparticles. PAMELA was launched with a Soyuz-U rocket on June 15th 2006 from the Baikonur cosmodrome in Kazakhstan. The apparatus is hosted on the Russian Resurs DK1 earth monitoring satellite. The orbit is elliptical (altitude varying between 355 and 584 km) and semipolar (inclination 69.9°) and has a period of 94 min. The mission is foreseen to last at least 3 years.

The main scientific aim of PAMELA is the study of the antimatter component of the cosmic radiation above the atmosphere. PAMELA searches for dark matter candidates through the detailed measurement of the antiproton and positron spectra. Figs. 1 and 2 show the current status of cosmic ray antiproton and positron measurements, compared to theoretical calculations. The scenarios with pure secondary production (solid and dotted lines) and with a contribution of primary production due to the annihilation of dark matter massive particles (supersymmetric neutralinos, dotted lines) are shown. The expectations for PAMELA are shown in both scenarios, with statistical error bars. PAMELA is also looking for antinuclei, in particular antihelium, with a sensitivity in the ratio $\overline{\mathrm{He}}/\mathrm{He}$ of the order of 10^{-7}, a factor 10 better than existing measurements. Detailed measurements of the antiproton and positron energy spectra will provide valuable information on cosmic-ray propagation and solar modulation, such as charge dependent solar modulation effects. Other scientific objectives include the study of solar physics (low-energy particles), of high-energy electrons up to few TeV and of light nuclei (up to $Z = 6$). Table 1 summarises the design goals for PAMELA performance.

2. The PAMELA apparatus

The PAMELA experiment consists of several subdetectors, each providing an independent measurement of the incident particles. The combination of detectors allows the energy and rigidity (=momentum/charge) of the particle to be measured, as well as the sign and absolute value of its charge, its mass and type (hadron or lepton). The subdetectors provide redundant information in order to evaluate systematic errors present in the measurements. Fig. 3 provides a schematic overview of the PAMELA experiment and shows the location of the subdetectors. PAMELA is built around a 0.43 T permanent magnet

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[1]PAMELA homepage: http://wizard.roma2.infn.it/pamela/.

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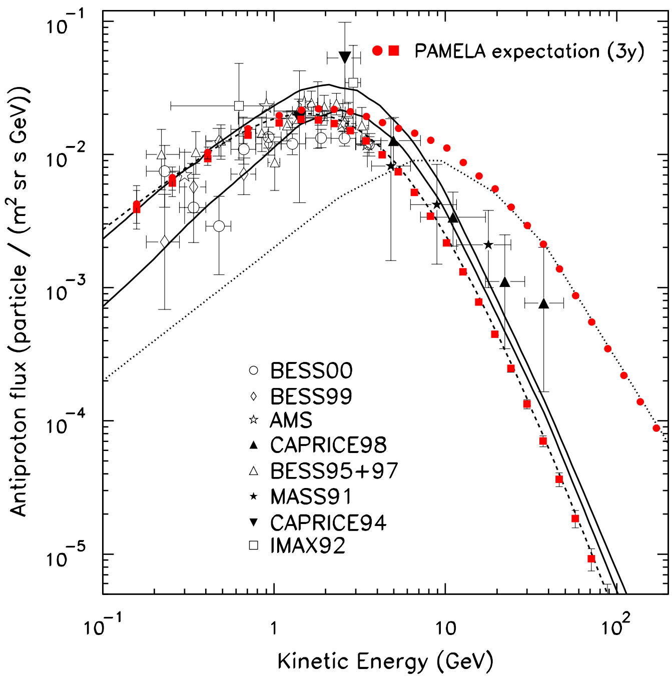

Fig. 1. PAMELA antiproton flux expectations after 3 years of data taking. The figure includes present data and PAMELA expectations in case of exotic contributions, with signal coming from the annihilation of a heavy neutralino, with mass 964 GeV (filled circles). Expectations without exotic contribution are also shown (filled squares). Present data and PAMELA expectations are plotted with error bars.

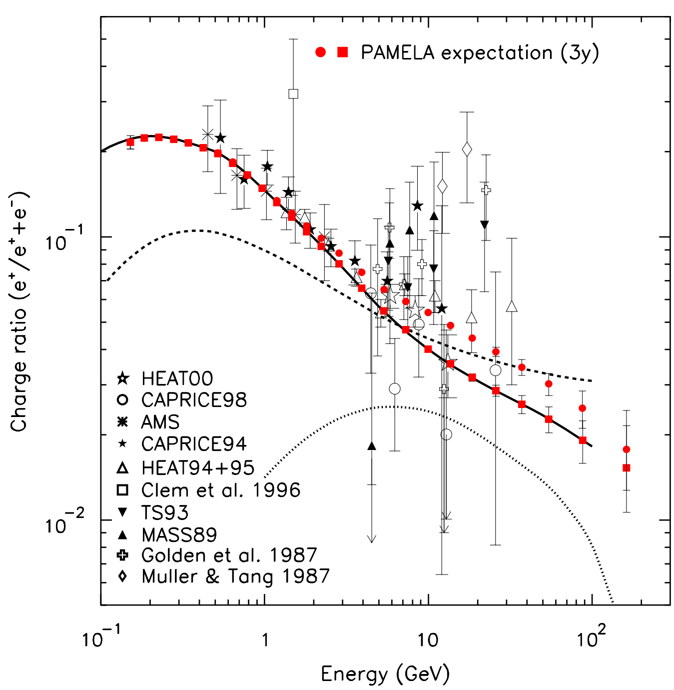

Fig. 2. The positron fraction ($e^+/e^+ + e^-$) is plotted for existing and future experiments, with signal coming from the decay of a neutralino with mass 336 GeV. The PAMELA expectations after 3 years of data taking are shown with (filled circles) and without (filled squares) the contribution from neutralino decay.

Table 1
PAMELA design goals after 3 years of data taking

Particle	Energy range
Protons	80 MeV–700 GeV
Antiprotons	80 MeV–190 GeV
Electrons	50 MeV–400 GeV
Positrons	50 MeV–270 GeV
Light nuclei ($Z \leqslant 6$)	100 MeV/n–700 GeV/n
$\overline{\mathrm{He}}$/He limit (90% c.l.)	$\sim O(10^{-7})$

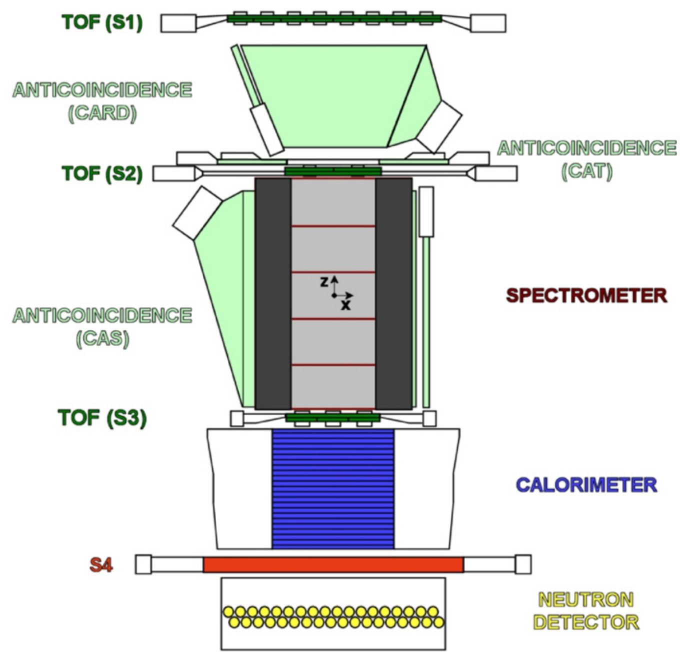

Fig. 3. Schematic view of the PAMELA apparatus. For a description of the subdetectors, see Section 2.

spectrometer (tracker) [2] equipped with six planes of double-sided silicon detectors. The acceptance of the spectrometer, which is the acceptance of the experiment, is $21.5\,\mathrm{cm}^2\,\mathrm{sr}$. The maximum detectable rigidity is $\sim$700 GV. The main task of the spectrometer is to measure the rigidity of the incoming charged particles. Below the tracker is placed the electromagnetic imaging calorimeter [3], whose main aim is the energy measurement of electrons and positrons. It is a highly segmented sampling calorimeter made of 22 silicon sensor planes interleaved with tungsten absorber plates, each 2.6 mm thick. The total thickness corresponds to 16.3 radiation lengths (X_0), i.e. about 0.6 interaction lengths. Another important calorimeter task is particle identification. Electromagnetic and hadronic showers develop differently in the calorimeter, allowing identification through shower analysis. The tail catcher scintillator (S4) and the neutron detector [4] measure highly energetic events not contained in the calorimeter and expand the energy range of the recorded primary protons and electrons up to $10^{11}-10^{13}$ eV. In order to increase the PAMELA geometrical acceptance at energies above 300 GeV, a self-trigger feature is implemented in the calorimeter. The trigger of the experiment comes from the time-of-flight (ToF) system [5], that consists of three segmented planes of fast scintillator detectors read-out by photomultiplier tubes (PMTs). The ToF system measures also the velocity of the particles (with a time resolution of 250 ps), enabling the rejection of albedo particles, and their charge (through energy loss dE/dx measurements). The sides of the magnet and of the region between the first two planes of the ToF system are surrounded by nine plastic scintillators read-out by PMTs forming the anticoincidence (AC) system [6]. The AC system can be used to reject particles not cleanly entering the acceptance of the experiment, but giving rise to coincidence deposited energy in the trigger scintillators (false triggers). Information from the AC system and from the calorimeter is implemented in a second level trigger, to reduce online the number of false triggers, and may be activated by an uplink command from ground [7].

The acquisition system is dimensioned to handle the maximum data volume generated by PAMELA (up to 20 GB/day). When a trigger is detected, the subdetectors are read-out sequentially. Data are 'down-loaded' into the satellite on-board memory and stored prior to be 'down-linked' to the ground station in Moscow.

3. PAMELA in-flight performance

After a short commissioning phase, PAMELA has been continuously acquiring data since July 11th. Data down-linked to ground shows that all PAMELA detectors are performing as expected. Fig. 4 provides a visual representation of the interaction of a 12.5 GV proton interacting in the calorimeter. While PAMELA aims at measuring galactic cosmic rays, the components of solar particle events (SEP) and trapped particles cannot be neglected. The scintillator detectors (part of the AC and ToF systems) have been used to study the particle fluxes above the atmosphere. Fig. 5 shows the rate (in Hz) of hits above threshold in one of the AC detectors as function of time for a representative orbit. The effect of the geomagnetic cut-off is evident. Low-energy particles are deflected away from the Earth in the equatorial regions before reaching PAMELA, while near the poles they reach lower altitudes and may be detected. The sudden increase in the rate is due to a passage through the South Atlantic Anomaly (SAA), where trapped particles account for an increase of up to ~100 times in the count rate compared to polar regions. The majority of trapped particles in the SAA are protons with energy up to few hundred MeV. The passages through the outer radiation belts, populated by electrons up to about 10 MeV, are also clearly distinguishable in the figure. In these high-rate regions neither the ToF detectors nor the

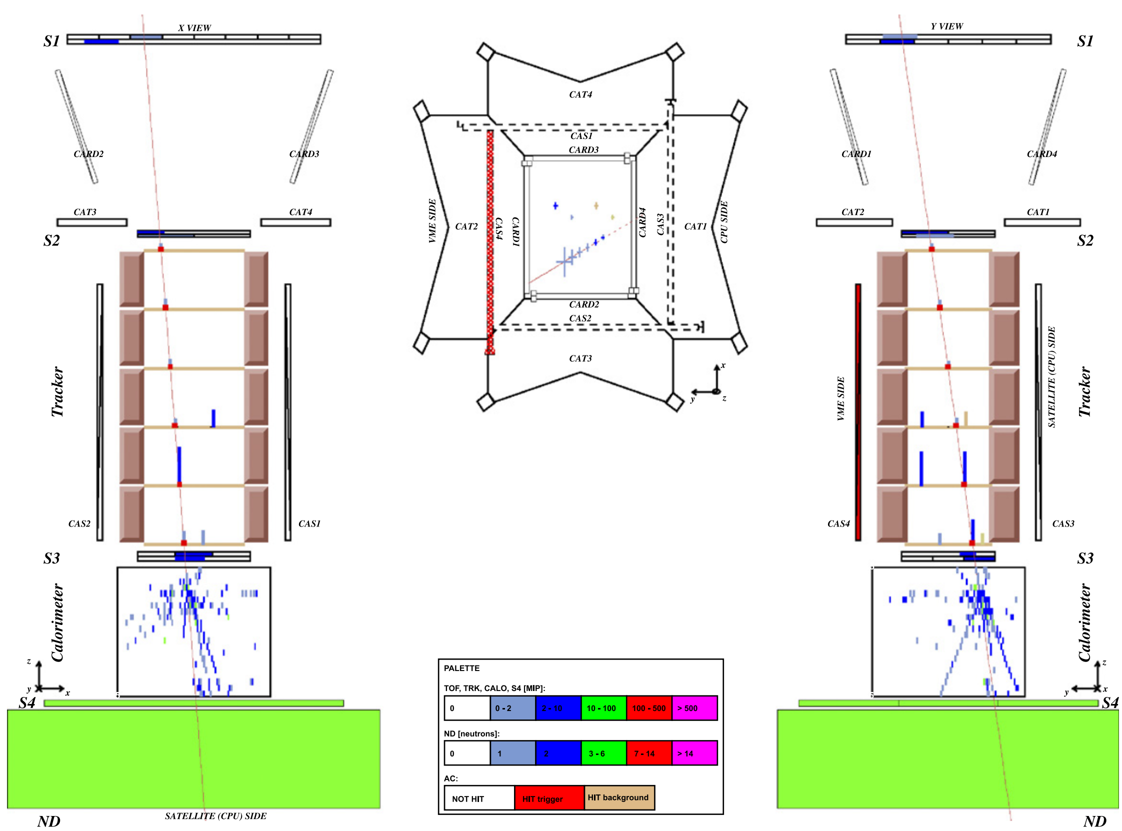

Fig. 4. Example of a reconstructed event in the PAMELA apparatus, corresponding to a 12.5 GV proton interacting in the calorimeter. A lateral anticoincidence detector is hit probably due to the interaction with a particle backscattered from the calorimeter.

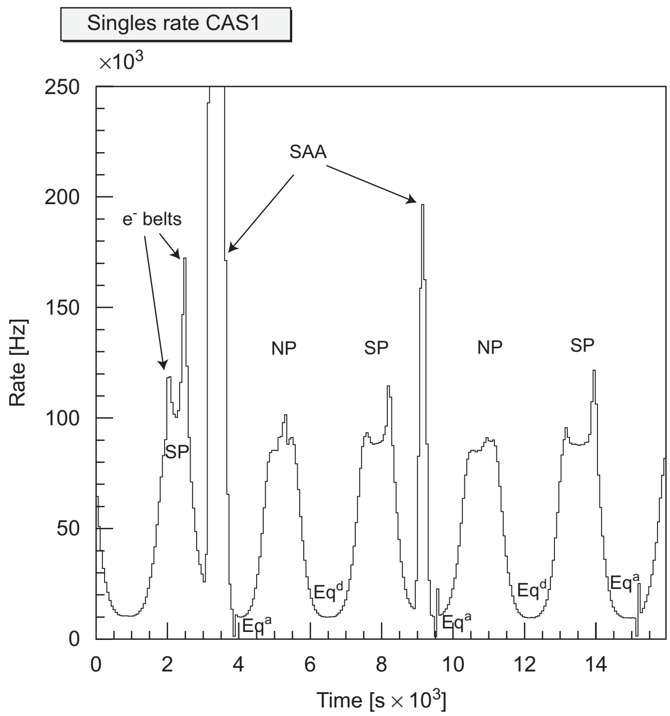

Fig. 5. Rate of an anticounter PMT as function of time (Hz). For the first orbit it is shown in which region PAMELA is located: North Pole (NP), Equator (Eq, ascending or descending node), South Pole (SP), electron belt or SAA. The peak out of scale in the figure reaches a maximum of 2 MHz and is due to the passage of PAMELA in the SAA. The feature on the equator ascending node (Eq[a]) depends on the on going calibration and has no physical significance.

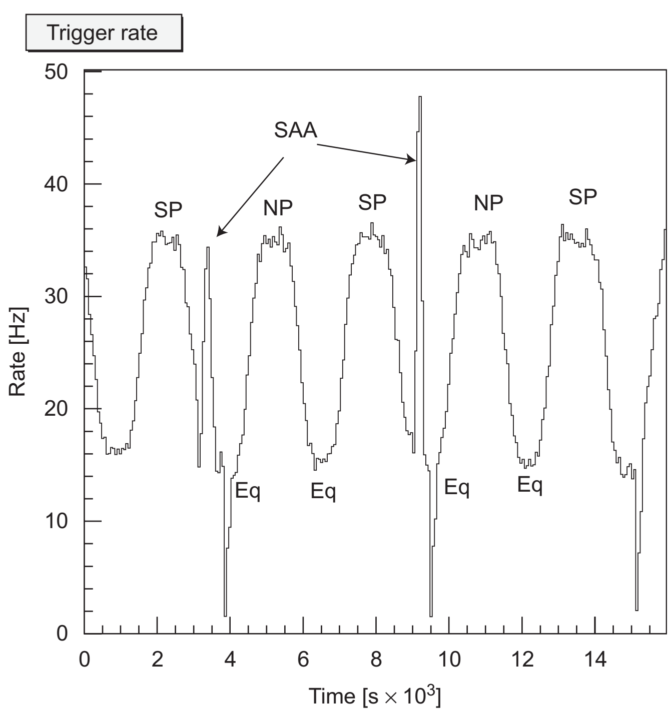

Fig. 6. Trigger rate for the PAMELA experiment for a representative run. The maxima at ~35 Hz correspond at the passages over the polar regions, the minima (16 Hz) to the equatorial regions. The South Atlantic Anomaly (SAA) is clearly visible as a sudden increase in the rate. The missing acquisition time corresponds to the detector calibration. The trigger configuration is changed depending on the orbital position.

AC detectors saturate, therefore their count rates may be used to continuously study the particle flux. In the SAA the trapped proton energy is at the lower limit of the acceptance of the experiment, but their flux is so high that different trapped particles may hit several trigger scintillators inducing a (false) trigger. This explains the trigger rate increase in correspondence of the SAA, shown in Fig. 6.

4. Conclusions

PAMELA is a satellite-based apparatus designed to study the charged component of the cosmic radiation in the energy range from below 100 MeV to several hundreds of GeV. PAMELA searches for dark matter candidates through the detailed measurement of the antiproton and positron spectra. Other scientific objectives include test of cosmic-ray propagation models, search for antinuclei and study of solar physics and solar modulation during the 24th solar minimum. The successful launch took place on June 15th 2006 and PAMELA has been in continuous data-taking mode since July 11th. The entire instrument is functioning as expected and up to 20 GB of data are transferred every day to the ground station in Moscow. The scintillator detectors of PAMELA (part of the anticoincidence and time-of-flight systems) have been used to study the particle rate in space as function of the orbital position.

Acknowledgments

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