Calorimetry in space with PAMELA

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on the behalf of the PAMELA collaboration†

The Payload for Antimatter-Matter Exploration and Light Nuclei Astrophysics (PAMELA), launched on June 15^{th}, 2006, has obtained significant results on cosmic-ray antiparticles (that can be interpreted in terms of dark matter annihilation or pulsar contribution). Moreover, precise particle spectra measurements made by PAMELA are challenging the standard acceleration and propagation paradigms. The calorimeter of the PAMELA apparatus was designed to identify antiprotons from an electron background and positrons from a background of protons, with high efficiency and rejection power. It is a sampling silicon-tungsten imaging calorimeter, which comprises 44 single-sided silicon sensor planes interleaved with 22 plates of tungsten absorber (0.74 X_0 each). In this paper we present the in-flight performance of the calorimeter (including a measured proton rejection factor of 10^5) and their impact on the science capabilities achieved by PAMELA.

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1. Introduction

PAMELA (a Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics) is a satellite-borne experiment designed to study charged particles in the cosmic radiation, with a particular emphasis on antiparticles, from tens of MeV up to hundreds of GeV. PAMELA was launched into space by a Soyuz-U rocket on June 15^{th}, 2006 from the Baikonur cosmodrome (Kazakhstan) [1]. The instrument has been observing cosmic rays since then: as of now, more than 10^{13} triggers have been registered and more than 30 TB of data have been downloaded.
The primary scientific goal of the mission was the study of the antimatter component of the cosmic radiation, in order to:

- Search for evidence of dark matter particle annihilations;
- Search for antinuclei (in particular, antihelium);
- Test cosmic-ray propagation models through precise measurements of the antiparticles energy spectra.

Other important scientific goals include: the study of solar physics and solar modulation during the 24^{th} solar minimum, and the study of the cosmic-ray electron energy spectrum up to several TeV, thereby allowing possible contributions from local sources to be identified.

2. The PAMELA apparatus

The PAMELA apparatus is $\sim$ 1.3 m high, has a total mass of 470 kg and an average power consumption of 355 W.
The central part of the apparatus is a magnetic spectrometer, consisting of a permanent magnet and a silicon tracker [2]. The magnet provides a uniform magnetic field of 0.43 T along the y direction. The dimensions of the cavity of the magnet define the geometrical factor of the experiment to be 21.5 cm^2 sr. The main task of the magnetic spectrometer is to measure particle rigidity $\rho = pc/Ze$ (p and Ze being respectively the particle momentum and charge, and c the speed of light) and ionization energy losses (dE/dx). The electromagnetic calorimeter, which will be described in next sections of this paper, is installed below the magnetic spectrometer.The Time-of-Flight (ToF) system of the experiment [3] provides a fast signal for triggering the data acquisition in the PAMELA subdetectors and performs up to 12 independent measurements of the particle velocity, $\beta = v/c$. By measuring the particle velocity the ToF system discriminates between downgoing and upgoing splash albedo particles, thus enabling the spectrometer to establish the sign of the particle charge. The ToF system also provides 6 independent dE/dx measurements, one for each scintillator plane. The aim of the anticoincidence (AC) system [4] is to identify false triggers and multiparticle events, generated by secondary particles produced in the apparatus. Below the electromagnetic calorimeter, a single square plastic scintillator (S4) acts as a shower-tail catcher and is used to generate a high energy trigger signal for the underlying neutron detector (ND) [5]. The purpose of the neutron detector is to complement the electron-proton discrimination capabilities of the calorimeter by detecting the increased neutron production associated with hadronic showers in the calorimeter compared with electromagnetic ones.
A more detailed description of the instruments and the data handling can be found in [1].

3. The electromagnetic imaging calorimeter

3.1 Physics tasks of the PAMELA calorimeter

The main task of the calorimeter is to select positrons and antiprotons from the large background constituted by protons and electrons, respectively. Positrons have to be identified from a background of protons that is about 10^3 times the positrons component at 1 GeV/*c*, increasing to $\sim 5\times 10^3$ at 10 GeV/*c*. Antiprotons have to be selected from a background of electrons that decreases from $\sim 5\times 10^3$ times the antiproton component at 1 GeV/*c* to less than 10^2 times above 10 GeV/*c*. This means that PAMELA must be able to separate electrons from hadrons at a level better than 10^5. Much of this rejection power is provided by the calorimeter. Besides the electron-hadron separation, the calorimeter must also directly measure the energy of electrons and positrons.

3.2 Calorimeter structure

The Imaging Calorimeter comprises 44 single-sided silicon strip detector planes interleaved with 22 plates of tungsten absorber [6]. Each tungsten layer is 0.74 X_0 thick (2.6 mm) and it is sandwiched between two printed circuit boards, which house the silicon detectors as well as the front-end and digitizing electronics. Each silicon plane consists of 3×3 detectors, each one 380 μm thick and with an active surface of 8×8 cm^2, segmented into 32 strips with a pitch of 2.4 mm. The orientation of the strips for two consecutive silicon planes is shifted by 90°, thus providing 2-dimensional spatial information. Each of the 32 strips is wire-bonded to the corresponding strip on the other two detectors in the same row (or column), thereby forming 24 cm long readout strips. The total depth of the calorimeter is 16.3 X_0 ($\sim 0.6\ \lambda_I$). The high granularity of the calorimeter and the use of silicon strip detectors provide detailed information on the longitudinal and lateral profiles of particles'interactions, as well as a measure of the deposited energy. The instrument is $\sim$21 cm tall and the sensitive area of the silicon planes is 24×24 cm^2.

3.3 Front-end and data acquisition electronics

The calorimeter front-end electronics is based on the CR1.4P full custom ASIC preamplifier [7]. A large dynamic range is of crucial importance for the calorimeter, in order to correctly measure the interactions of high energy particles. The CR1.4P was therefore designed to provide a wide dynamic range ($\sim$ 1400 Minimum Ionizing Particles, or about 7.1 pC for 380 μm thick silicon detectors). This ASIC has also a good signal-to-noise ratio for 1-MIP signals ($\sim$ 9:1) notwithstanding the rather large ($\sim$ 180 pF) capacitance presented at its input by the 24 cm long calorimeter strips. Six CR1.4P chips are used to read-out each silicon plane.In each plane, the analog outputs of the front-end chips are multiplexed into a single 16-bit ADC (Analog Devices AD977A).
Data from all 44 ADCs are processed by 4 read-out boards mounted on the front cover of the calorimeter. Four FPGA (Altera A54SX72), one per section, control all data acquisition and slow control processes and, in normal acquisition mode, transmit the data to 4 DSPs (Analog Devices ADSP2187), which perform the tasks of first-level data analysis, compression and on-line calibration. More details on the calorimeter read-out electronics can be found in [1] and [8].

4. Physics performance

As mentioned in section 3, the imaging calorimeter of PAMELA has been designed to precisely reconstruct the longitudinal and lateral profiles of interactions and to measure the deposited energy. The longitudinal and lateral segmentation of the calorimeter, combined with the measurement of the particle energy loss in each strip, allows a very high identification power for electromagnetic showers. The e/h discrimination power of the calorimeter is obviously fundamental for data analysis, especially for the extraction of the positron signal from the proton background. An example of the calorimeter capabilities in the positron selection is illustrated in Fig. 1. Left part of Fig. 1 shows the distribution of the ratio between the charge released along the track in the calorimeter (obtained by summing the signal in the hit strip and the signals in the left and right neighboring strips) and the total charge measured in the calorimeter for two samples of flight data (positive and negative, with rigidity between 20 and 30 GV, as selected by the magnetic spectrometer). In these plots, non-interacting antiprotons and protons are clearly seen, peaked at one. In the negative plot the electrons distribution is clearly seen (due to the paucity of the antiprotons), while in the positive plot the positron sample (expected to be peaked at an energy fraction corresponding to that of the electrons) is completely overwhelmed by the background of interacting protons. To obtain right part of Fig. 1 a set of high-efficient selections (energy-momentum match and topological cuts) are imposed: the positron sample became clearly visible. It should be noted that the above mentioned cuts are just an example to show calorimeter capabilities in e/h separation. In the positron data analysis, additional topological and energy-related conditions are used.

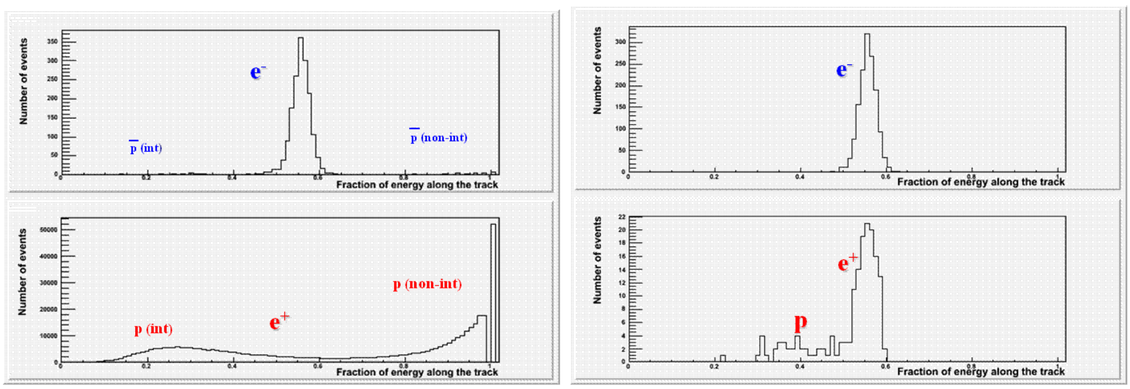

Figure 1: (*left*) Plot of the energy fraction released along the track in the calorimeter for both negative (top) and positive (bottom) charge in the rigidity interval 20 ÷ 30 GV. (*right*) The same distributions after applying an energy-momentum match condition and topological cuts related to the shower profile.

The excellent positron discrimination capabilities of the calorimeter have been fully exploited in the measurement of the galactic cosmic ray positron flux [9]. Results, presented in figure 2, are in agreement with previous measurements and confirm that the increase in the positron fraction is due to a positron signal rather than a softer electron spectrum.

5. Conclusions

The satellite-borne experiment PAMELA has been studying cosmic rays for more than seven

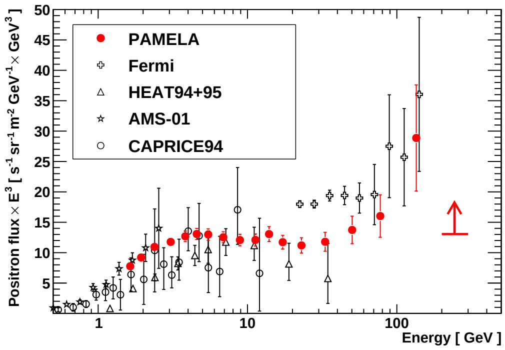

Figure 2: PAMELA positron flux compared to previous measurements.

years. Throughout this period, the Si-W imaging calorimeter of the apparatus has been performing nominally. In particular, all functional parameters are nominal and stable. The physics performance are consistent with the expectations, with the simulations and test beam results. Actually no failures nor significant loss/degradation of performance have been observed and the calorimeter proved to be able to fulfill the requirements needed to achieve the scientific goals of PAMELA.

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