Understanding Cosmic Rays and Searching for Dark Matter with PAMELA

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DOI: http://dx.doi.org/10.3204/DESY-PROC-2010-03/sparvoli_roberta

After four years of data taking in space, the experiment PAMELA is showing very interesting features in cosmic rays that might change our basic vision of their mechanisms of production, acceleration and propagation in the galaxy. In addition, PAMELA measurements of cosmic antimatter fluxes are setting strong constraints to the nature of dark matter. In this paper PAMELA main results will be briefly reviewed.

1 PAMELA physics goals and instrument description

PAMELA was conceived as a cosmic ray observatory placed at 1 Astronomical Unit; its 70 degrees, 350–610 km quasi–polar elliptical orbit, indeed, makes it particularly suited for studying cosmic rays of galactic, heliospheric and trapped nature.

PAMELA best capabilities are expressed in the high–precision spectral measurement of antiprotons and positrons, and in the search for antinuclei in the cosmic radiation, over a wide energy range. Besides the study of cosmic antimatter, the high–identification capabilities of the instrument allow light nuclei and their isotopes, at least up to Z=8, to be identified. This provides complementary data, besides antimatter abundances, to test models for the origin and propagation of galactic cosmic rays, and to investigate the nature of dark matter.

The instrument is installed inside a pressurized container attached to the Russian Resurs–DK1 Earth observation satellite that was launched into Earth orbit by a Soyuz–U rocket on June 15^{th} 2006 from the Baikonur cosmodrome in Kazakhstan. The mission is foreseen to last till at least December 2011.

The PAMELA apparatus comprises the following subdetectors: a time–of–flight system, a magnetic spectrometer, an anticoincidence system, an electromagnetic imaging calorimeter, a shower tail catcher scintillator and a neutron detector. The timing resolution of the TOF system allows albedo–particle identification and mass discrimination below 1 GeV/c. The magnetic spectrometer consists of a 0.43 T permanent magnet and a silicon tracking system, composed of 6 planes of double–sided microstrip sensors. The acceptance of the spectrometer, which also defines the overall acceptance of the PAMELA experiment, is 21.5 cm^{2}sr and the spatial resolution of the tracking system is better than 4 μm up to a zenith angle of 10°, corresponding to a maximum detectable rigidity (MDR) exceeding 1 TV. The electromagnetic calorimeter ha 16.3 X_0 and 0.6 $\lambda 0$, and allows topological discrimination between electromagnetic and hadronic showers, or non–interacting particles. More technical details about the PAMELA instrument

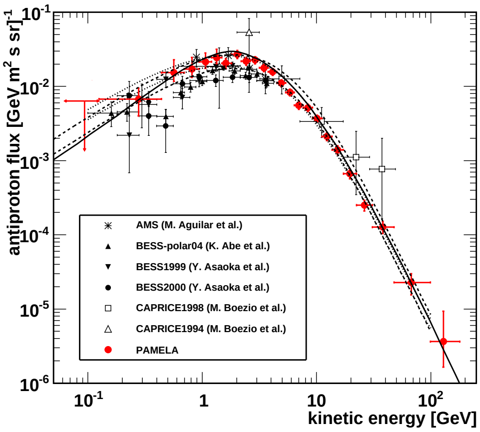

Figure 1: The antiproton energy spectrum at the top of the payload compared with contemporary measurements [3, 4, 5, 6, 7] and theoretical calculations for a pure secondary production [8, 9].

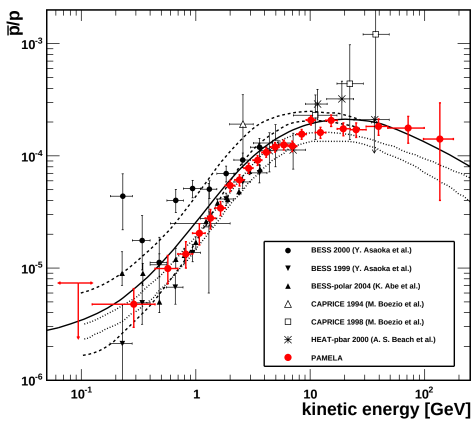

Figure 2: The antiproton-to-proton flux ratio at the top of the atmosphere compared with contemporary measurements [3, 4, 5, 6, 10] and theoretical calculations for a pure secondary production [11, 12, 9].

and launch preparations can be found in [1].

PAMELA was first switched on June 21^{st} 2006 and it has been collecting data continuosly since July 11^{th} 2006. To date, about 1600 days of data have been analyzed, corresponding to more than two billion recorded triggers and about 20 TB data.

2 PAMELA results: Antiprotons

In 2009 the PAMELA collaboration presented the antiproton-to-proton flux ratio in the kinetic energy range between 1.5 and 100 GeV [2], and this was found to follow the expectations from secondary production calculations. In 2010 we extended the data set collected, and we obtained the antiproton absolute spectrum from 60 MeV to 180 GeV - the widest energy range ever achieved - and the antiproton-to-proton flux ratio across the same energy interval [14]. Figure 1 shows the antiproton energy spectrum and figure 2 shows the antiproton-to-proton flux ratio measured by PAMELA along with other recent experimental data and theoretical calculations assuming pure secondary production of antiprotons during the propagation of cosmic rays in the galaxy. The curves were calculated for solar minimum, which is appropriate for the PAMELA data taking period, using the force field approximation [13].

The PAMELA results reproduce the expected peak around 2 GeV in the antiproton flux (due to the kinematic constraints on the antiproton production) and are in overall agreement with pure secondary calculations. The experimental uncertainties are smaller than the spread in the different theoretical curves and, therefore, provide important constraints on parameters relevant for secondary production calculations. Comments about a possible exotic contribution compatible with PAMELA antiproton data are given in [14].

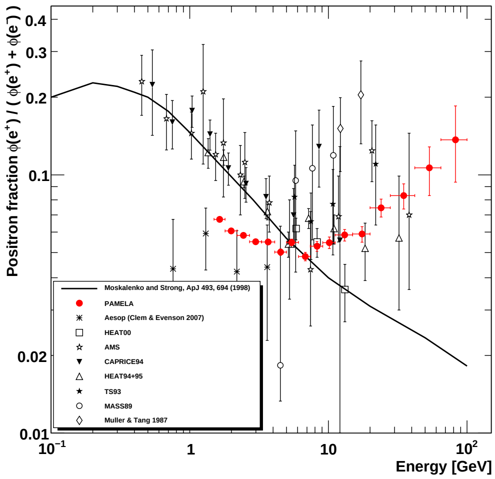

Figure 3: The positron fraction measured by the PAMELA experiment, compared with other recent experimental data [15], and a theoretical calculation [16].

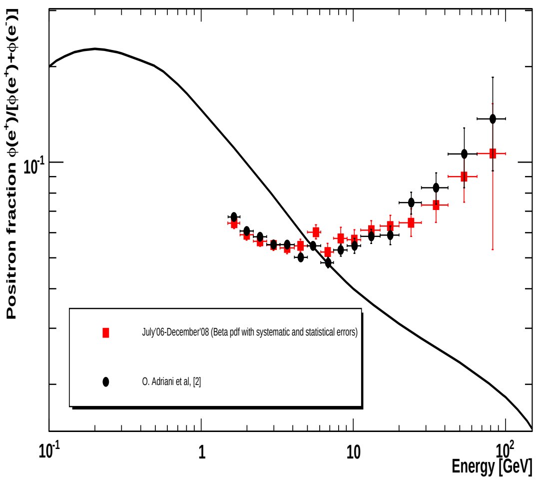

Figure 4: The positron fraction obtained using a beta-fit with statistical and systematic errors summed in quadrature (red) [17], compared with the fraction reported in fig. 3.

3 PAMELA results: Positrons

The positron to all electron (i.e. electron + positron) ratio measured by the PAMELA experiment is given in fig. 3, compared with other recent experimental results and with a theoretical calculation [15]. The data, covering the energy range 1.5 - 100 GeV, show two clear features. At low energies, below 5 GeV, the PAMELA results are systematically lower than data collected during the 1990's; this can be convincingly explained by effects of charge-dependent solar modulation. At high energies, above 10 GeV, data show a positron fraction increasing significantly with energy, contradicting the expectations.

Results published in [15] refer to data collected by PAMELA between July 2006 and February 2008. Afterwards, we analyzed a larger data set and we applied a different statistical methodology [17] for the determination of the background in the positron sample.

Fig. 4 shows the positron fraction obtained through a beta-fit with statistical and systematic errors summed in quadrature, compared with the PAMELA positron fraction of fig. 3. The new experimental results are in agreement with what reported in [15] and confirm both solar modulation effects on cosmic-rays with low rigidities and an anomalous positron abundance above 10 GeV. Various hypotheses about the nature of this exciting and unexpected increase at high energy have been proposed. The most interesting is connected with the annihilation of dark matter, even if astrophysical sources such as pulsars could contribute in part to the observed flux of positrons. A review of possible hypothesys is given in [18].

It is worth to note that a physical process creating a positron from a zero charge system also implies the creation of a corresponding electron. Therefore an exotic source of positrons in our Galaxy is presumably also a source of electrons. PAMELA collaboraton is working to provide measurements of the electron, positron and "all-electron" spectra. Results will be ready for

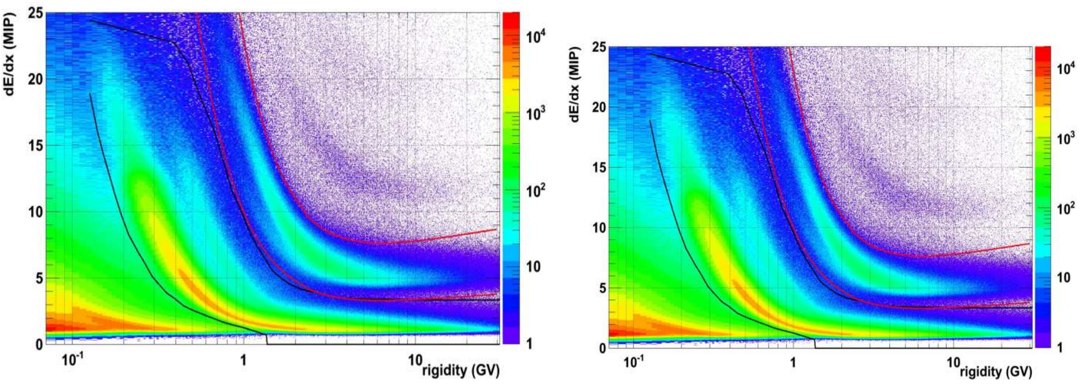

Figure 5: Left: Energy loss in tracker vs. tracker rigidity for positively charged particles. The proton and helium bands are clearly visible: the black and red lines represent the cuts used to select protons and heliums. Right: Capability of the Time-Of-Flight scintillators to separate the different charges as a function of velocity (beta), from proton to Oxygen.

publication by Fall 2010.

4 PAMELA results: Astrophysics Background

An accurate theoretical modeling of the fluxes of secondary species as antiprotons and positrons, produced by interaction of cosmic rays nuclei with the interstellar medium, is the starting point to highlight the presence of components produced by exotic sources such as dark matter. PAMELA is measuring with good precision and high statistics protons, ^{4}He, Carbon and Oxygen (primaries) together to ^{3}He, Li, Be, B (secondaries). These data constrain existing production and propagation models, providing detailed information on the galactic structure and the various mechanisms involved.

Figure 5, left, shows the energy loss in the PAMELA tracker versus the rigidity for positively charged particles. The proton and helium bands are clearly visible. On the right, instead, the capability of the TOF scintillators to separate the different charges, from proton to oxygen, is shown. Proton, helium and light nuclei fluxes measured by PAMELA are currently in publication, and they cannot be reported in this paper. However, by the end of 2010 PAMELA will have released to the scientific community the most comprehensive collection of cosmic matter and antimatter data ever acquired in space, across the widest energy range.

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