WIZARD/PAMELA

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1 The satellite mission PAMELA

PAMELA, a part of the WIZARD international experimental program on balloon, satellite and Space Station activities, is a cosmic ray space experiment installed and running on board a Russian satellite (Resurs-DK1) which has been successfully launched on June 15th, 2006 from the cosmodrome of Baikonur, Kazakhstan, by a Soyuz TM2 rocket.

The satellite is flying in a low altitude, elliptic orbit (350-610 km) with an inclination of 70.0 degrees. The PAMELA telescope consists of a magnetic spectrometer composed of a permanent magnet coupled to a silicon tracker, an electromagnetic silicon-tungsten calorimeter, a time-of-flight system, an anticoincidence system, a shower tail catcher scintillator and a neutron detector [1, 2].

The total height of PAMELA is ~ 130 cm, the mass is 470 kg and the power consumption is 355 W.

The observational objectives of the PAMELA experiment are to measure the spectra of antiprotons, positrons and nuclei in the cosmic rays over an extended range of energies, to search for antimatter and for indirect signatures of dark matter and to study cosmic ray fluxes over a significant portion of the Solar cycle.

The main scientific goals can be schematically listed as follows:

a) measurement of the antiproton spectrum in the energy range 80 MeV-190 GeV;
b) measurement of the positron spectrum in the energy range 50 MeV-300 GeV;
c) measurement of the electron spectrum up to 500 GeV;
d) measurement of the proton spectrum up to 700 GeV;
e) measurement of the electron+positron spectrum up to ~ 1 TeV;
f) measurement of light nuclei spectra (He/Be/C) up to 200 GeV/n;
g) search for antinuclei with a sensitivity of 3×10^{-8} in the $\overline{He}/He$ ratio.

Additional objectives achievable all over the duration of the mission are:
- Long-term monitoring of the solar modulation of cosmic rays;
- Measurements of Energetic Particles from the Sun;

- High-energy Particles in the Earth magnetosphere and Jovian electrons.

2 PAMELA Main results

After almost seven years of operation, both the satellite and the PAMELA instrument have shown to be properly functioning and the performance of the detectors to be fairly good. Every day, an average of 14 GBytes of data are transmitted to the main Receiving Station NTsOMZ located in Moscow where quick-look and first control of the performances of the instrument are performed. Then, all data are transferred through high-speed networks to CNAF, Bologna and to the participating institutions of the PAMELA International Collaboration for the full analysis of data. PAMELA, at present, has collected some 33 TBytes of data corresponding to about 3.5 billion events.

Due to the overall good performance of both the satellite and the instruments on board, and according to the latest agreements between the Russian Space Agency Roscosmos and INFN for the extension of the mission of one more year, PAMELA will continue running and taking data in 2013 (the mission was initially planned for three years).

2.1 Antiprotons

The antiproton energy spectrum and the antiproton-to-proton flux ratio measured by PAMELA [3] in the energy interval between 60 MeV and 180 GeV are shown respectively in Fig.1 and Fig.2, along with other recent experimental data and theoretical calculations done 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 [4]. The PAMELA results are in agreement with the previous measurements. They 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 a pure secondary production. The experimental uncertainties are smaller than the spread in the different theoretical curves and, therefore, the data provide important constraints on parameters relevant for secondary production calculations. However, a possible contribution from non thermally produced dark matter annihilation is suggested by some authors [5].

2.2 Positrons

The positron to all electron (i.e. electron + positron) ratio measured by the PAMELA experiment [6] is given in Fig.3, compared with other recent experimental results.

The calculation, shown in the same figure, for pure secondary production of positrons during the propagation of cosmic rays in the Galaxy without re-acceleration processes provides evidence that the positron fraction is expected to fall as a smooth function of increasing energy if secondary production dominates. 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 1990s; this can be convincingly explained by effects of charge-dependent solar modulation. At high energies, above 10 GeV, data show a positron fraction significantly increasing with energy. The background propagation model considered in Fig.3 is clearly not able to fully account for the experimental data. In particular, the rising at $E > 10$ GeV seems a very difficult feature to be reproduced by a pure secondary component without using an unrealistic soft electron spectrum [7], suggesting the existence of other primary sources [8].

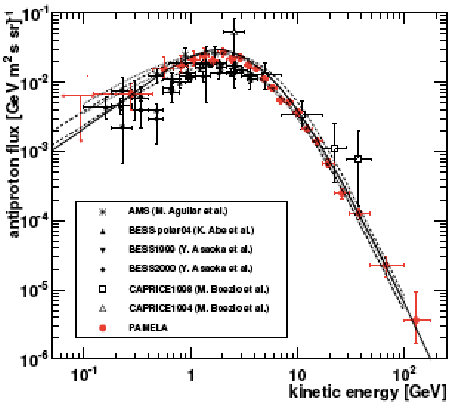

Figure 1: The PAMELA antiproton energy spectrum compared with recent measurements (see references in [3]).

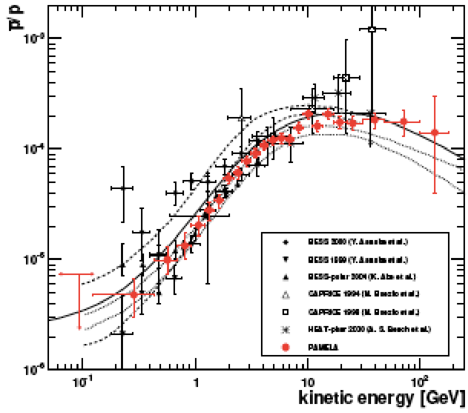

Figure 2: The PAMELA antiproton-to-proton flux ratio compared with recent measurements (see references in [3]).

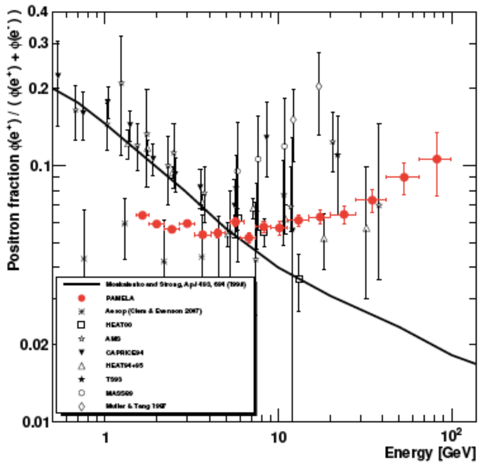

Figure 3: The PAMELA positron fraction compared with other recent experiments (see references in [6]).

The most problematic theoretical challenge posed by the PAMELA results is the asymmetry between leptonic (positron fraction) and hadronic (antiproton-proton ratio) data, difficult to explain in the framework in which the neutralino is the dominant dark matter component. A suitable explanation requires a very high mass (M >10 TeV) neutralino [9], which is unlikely in the context of allowable energy supersymmetry breaking models. Better descriptions are obtained in terms of leptonic annihilation channels for a wide range of the WIMP masses [9]. Furthermore, all explanations in terms of dark matter annihilation require a boost factor for the annihilation standard rate ranging between 10^2 to 10^3. Among the models proposed to explain the PAMELA data, it is worth to cite also the Kaluza-Klein (KK) dark matter [10], in the Universal Extra Dimension framework. Besides particle physics interpretations, a variety of astrophysical models have been put forward to explain the positron excess. One plausible explanation relates to a contribution from nearby and young pulsars, objects well known as particle accelerators. Only a few months before the publication of PAMELA positron data, the ATIC collaboration reported an excess in the galactic all electron (sum of electrons plus positrons) energy spectrum at energies of $\sim 500 - 800$ GeV [11], which led to the speculation over the existence of a nearby source of energetic electrons, either of astrophysical or exotic nature. Later in 2009, the Fermi collaboration released results about the all electron spectrum up to 1 TeV [12]. Fermi high precision data show that this spectrum falls with energy as $E^{-3.0}$ - harder than the conventional diffusive model - but does not exhibit the same prominent spectral features of ATIC. The significant flattening of the Fermi data may suggest the presence of one or more local sources of high energy CR electrons, but also dark matter scenarios cannot be excluded. Many different articles appeared, which took into account in the same theoretical frame the data from PAMELA, ATIC and Fermi.

2.3 Proton and Helium spectra

PAMELA has measured the absolute cosmic ray proton and helium spectra [13] in the rigidity interval between 1 GV and 1.2 TV (Fig.4). The results are consistent with those of other experiments within the statistical and systematic uncertainties. The differences at low energies ($<$ 30 GeV) are caused by solar modulation effects. PAMELA results overlap with ATIC-2 data [14] between $\sim$ 200 and $\sim$ 1200 GV, but differ both in shape and absolute normalization at lower energies. The extrapolation to higher energy of the PAMELA fluxes suggest a broad agreement with those published by CREAM [15] and JACEE [16] but are higher than the RUNJOB [17] helium data. To gain a better understanding of the spectra, the results have been re-analyzed in terms of rigidity instead of kinetic energy per nucleon (Fig.5). Two important conclusions can be drawn from the PAMELA data.

Firstly, the proton and helium spectra have different spectral shapes. If a single power law is fit to the data between 30 GV and 1.2 TV, the resulting spectral indices show a significant difference. Secondly, the PAMELA data show clear deviations from a single power law model. The spectrum of protons gradually softens in the rigidity range 30 - 230 GV. At 230 - 240 GV the proton and Helium data exhibit an abrupt spectral hardening. This hardening could be interpreted as an indication of different populations of cosmic ray sources. Analysis of further data is in progress and more details of these results and of the analysis procedure can be found in [13].

2.4 Geomagnetically trapped cosmic-ray antiprotons around Earth

The most recent major result obtained by PAMELA is the observation - for the first time - of antiprotons trapped in Earth's inner radiation belt [18]. The antiparticle population originates from CR interactions in the upper atmosphere and subsequent trapping in the magnetosphere.

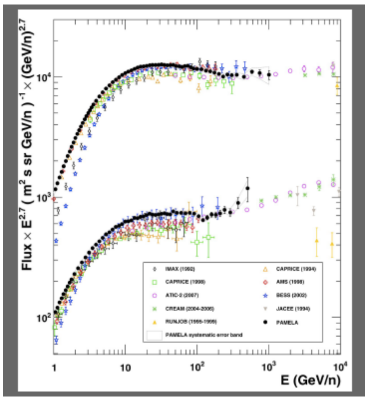

Figure 4: Proton (top points) and Helium (bottom points) absolute fluxes measured by PAMELA above 1 GeV/n compared with previous experiments (see details and references in [13]).

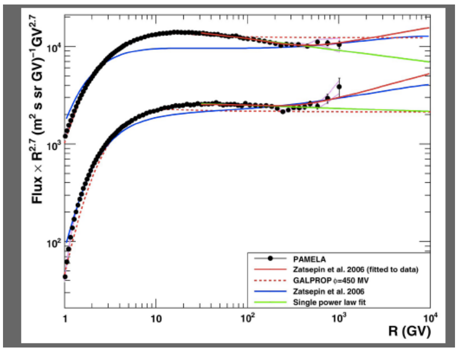

Figure 5: Proton (top points) and Helium (bottom points) data measured by PAMELA in the rigidity range 1 GV - 1.2 TV. The shaded area represents the estimated systematic uncertainty (see details and references in [13]).

PAMELA data confirm the existence of a significant antiproton flux in the South Atlantic Anomaly (SAA) region below ~ 1 GeV in kinetic energy, as shown in Fig.6.

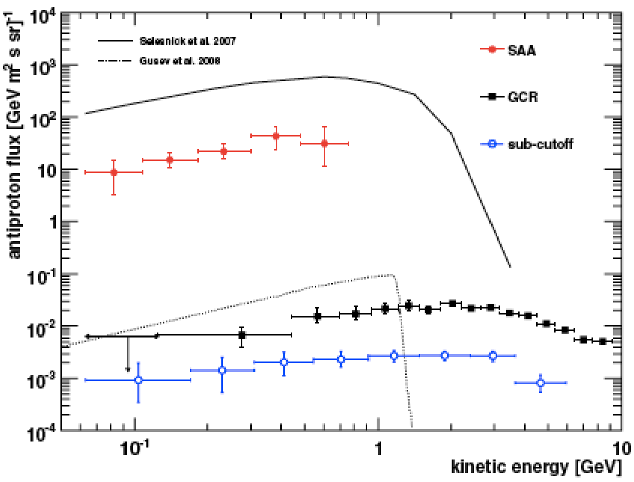

Figure 6: Geomagnetically trapped antiproton spectrum measured by PAMELA in the SAA region (red full circles). The error bars indicate statistical uncertainties. Trapped antiproton predictions by [19] for the PAMELA satellite orbit (solid line), and by [20] at L-shell = 1.2 (dotted line), are also reported. For comparison, the mean atmospheric under-cutoff antiproton spectrum outside the SAA region (blue open circles) and the galactic CR antiproton spectrum (black squares) measured by PAMELA ([3]) are also shown.

The flux exceeds the galactic CR antiproton flux by three orders of magnitude at the current solar minimum, thereby constituting the most abundant antiproton source near the Earth.

A measurement of the sub-cutoff antiproton spectrum outside the SAA region is also reported. PAMELA results allow CR transport models to be tested in the terrestrial atmosphere and significantly constrain predictions from trapped antiproton models, reducing uncertainties concerning the antiproton production spectrum in Earth's magnetosphere.

2.5 Solar events observation by PAMELA

The wide interval of measured energies makes PAMELA a unique instrument for solar energetic particle (SEP) observations filling the energy gap between the highest energy particles measured in space and the ground-based domain. Furthermore, these data can be used to study the effect of solar modulation in great detail. Since the start of Solar Cycle 24, PAMELA has observed and collected data during several solar events. A new collaboration for joint analysis of PAMELA data in comparison with other dedicated space missions has been established with the New Mexico State University, the University of New Hampshire and the NASA Goddard Space Flight Center. Data analysis is in progress and the extension of the PAMELA mission for one more year in 2013 will contribute to increase the statistics over a relevant part of an entire solar cycle.

3 Activity of the LNF group during year 2012 and for 2013

The LNF PAMELA group has been fully involved in all the previous balloon and present satellite programs in the design, prototyping, test and instrumental R&D for space. During the year 2012 the LNF group has continued the activity in the analysis, running and quick-look control of the mission. In particular, it is fully involved in the analysis of solar events (Solar Flares, SEP, Forbush decrease) which is also the argument of a doctoral thesis. The same activity will continue in 2013, including presentations at the International Cosmic Ray Conference (ICRC 2013), Rio de Janeiro. Final publications are expected from the analysis of the latest data.

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