



The Physics of PAMELA Space Mission

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Abstract: The Space Mission PAMELA, launched in orbit on June 15th 2006, represents the state-of-the-art of the investigation of the cosmic radiation to addressing the most compelling issues facing astrophysics and cosmology: the nature of the dark matter that pervades the universe, the apparent absence of cosmological antimatter, the origin and evolution of matter in the galaxy. The primary scientific goal of the Pamela investigation is the search for evidence of non baryonic particles falling outside Standard Model particle physics and of heavy antinuclei. Concomitant, but not secondary, goals are the study of the energy dependence of cosmic ray lifetimes in the Galaxy, the validation of models of acceleration, transport and secondary production of cosmic radiation in the Galaxy, the monitoring of the solar activity and the knowledge of the role of solar and terrestrial relationships in the energetic particle propagation in the heliosphere. The observational objectives are the measurements of the fluxes and the energy spectra of antiprotons, protons, positrons, electrons and light nuclei in a very large energy range and the search for antinuclei with a sensitivity of the order of 10^{-8} in $\bar{\text{He}}/\text{He}$.

Introduction

The satellite-based PAMELA experiment [1] (a ‘Payload for Antimatter–Matter Exploration and Light-nuclei Astrophysics’) was launched into space in a semipolar (70°) elliptical (350×600 km) orbit on the 15th June 2006 by a Soyuz-U rocket from the Baikonur cosmodrome in Kazakhstan. PAMELA is installed inside a pressurised container attached to the Russian Resurs-DK1 Earth-observation satellite. After a short commissioning phase, PAMELA has been in a nearly continuous data taking mode since July 11th 2006. PAMELA is a powerful particle identifier composed of a permanent magnet spectrometer with a variety of specialized detectors. The apparatus is able to measure with unprecedented statistics and sensitivity abundances and energy spectra of cosmic rays over a very large range of energy (50 MeV–400 GeV for electrons, 50 MeV–270 GeV for positrons, 80 MeV–700 GeV for protons, 80 MeV–190 GeV for antiprotons, up to 200 GeV/n for light nuclei and up to 2 TeV for e^-+e^+). The PAMELA mission is devoted to the investigation of dark matter, the baryon asymmetry in the Universe, cosmic ray generation and propagation in our galaxy and the solar system, and to the study of solar modulation and interaction of cosmic rays with the Earth’s magnetosphere.

Preliminary in-flight results from the various detectors are described elsewhere in these proceedings [2].

The Science of PAMELA

The primary scientific goal of the PAMELA experiment is the study of the antimatter component of the cosmic radiation, in order: 1. to search for antinuclei, in particular antihelium; 2. to search for evidence of annihilations of dark matter particles by accurate measurements of the antiproton and positron energy spectra; 3. to test cosmic-ray propagation models through precise measurements of the antiproton and positron energy spectra and precision studies of light nuclei and their isotopes.

Concomitant goals include: 1. a study of solar physics and solar modulation during the 24th solar minimum; 2. a study of trapped particles in

the radiation belts. The semipolar orbit allows PAMELA to investigate a wide range of energies for the different antiparticles, particles and nuclei. Three years of data taking will provide unprecedented statistics in these energy ranges with no atmospheric overburden, consenting to greatly reduce the systematic errors of the balloon measurements, and to explore for the first time the \bar{p} and e^+ energy spectra well beyond the present limit of experimental data (~ 40 GeV).

Antimatter and Dark Matter

The study of antimatter and antiparticle content in cosmic rays is a unique tool to investigate several physics and astrophysical phenomena. The idea of performing cosmic antiproton and positron measurements to probe unconventional particle physics and astrophysics scenarios has a long history (see references in [3]) and moved the cosmologists for several decades. The search of antimatter is instead strictly connected with the baryon antibaryon asymmetry in the Universe. Therefore, detection of antimatter of primary origin in cosmic rays would be a discovery of fundamental significance. If there was primordial antimatter, antihelium would be the most likely form to be detected in cosmic rays, likewise in matter primordial nucleosynthesis in which helium is the next most abundant element to hydrogen. The present observational limit in the search of antihelium is in the order of 10^{-6} in the $\overline{\text{He}}/\text{He}$ ratio. PAMELA will extend this limit to the $\sim 10^{-8}$ level. The detection of antinuclei with $Z>2$ in cosmic rays would provide, instead, direct evidence of the existence of antistellar nucleosynthesis. Antiprotons and positrons are not direct indicators for the existence of antimatter domains, because they are primarily produced by collisions of the cosmic rays with the ISM. The signature of antiprotons and positrons coming from distant antigalaxies would appear as a distortion on the detected secondary production fluxes.

Evaporation by the Hawking process of primordial black holes, produced very early in the hot Big Bang, in the quantum gravity era, and exotic particles annihilation might give other possible contributions. The search and the identification of such possible sources is one of the major challenges in

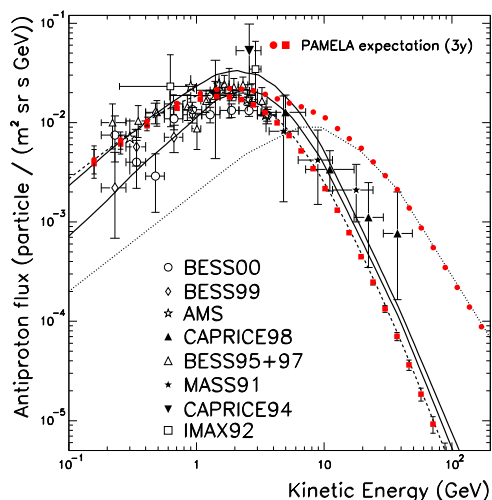


Figure 1: Recent experimental data for \bar{p} spectra along with theoretical calculations for pure \bar{p} secondary production (solid [4] and dashed [5] lines) and for pure primary production from a $964 \text{ GeV}/c^2$ neutralino (dotted line [6]). The PAMELA expectations after three years of data taking are shown in the cases a neutralino contribution is present (filled red circles) or absent (filled red squares). Only statistical errors are included in the expected PAMELA data.

cosmic rays studies. In fact several observations give us a coherent picture of a Universe dominated by dark matter and dark energy. In recent years cosmological observations have provided increasingly convincing evidence that non-baryonic dark matter is the building block of all structures in the Universe.

Among the most plausible candidates are weakly interacting massive particles (WIMP) of which the supersymmetric neutralino is a favourite candidate from the point of view of particle physics. The neutralino arises naturally in supersymmetric extensions of the standard model, and has the attractive feature of giving a relic density adequate to explain cosmological dark matter in a large region of the parameter space. Neutralinos are Majorana fermions and will annihilate with each other in the halo, resulting in the symmetric production of particles and antiparticles, the latter providing

an observable signature that will appear as a distortion on the secondary fluxes. The current status of the antiproton (positron) measurements is shown in figure 1 (2) and compared with PAMELA expectations after three years of data taking, with and without the contribution from the annihilation of a massive dark matter neutralino. Possibilities for dark matter detection in the antiproton and positron channels depend strongly on the nature of dark matter, its annihilation cross section and the local inhomogeneity of their distribution. The most interesting energy range of this search is the region above $\sim 10 \text{ GeV}$, where the excellent performances of Pamela are combined with the small influence of the solar modulation effects.

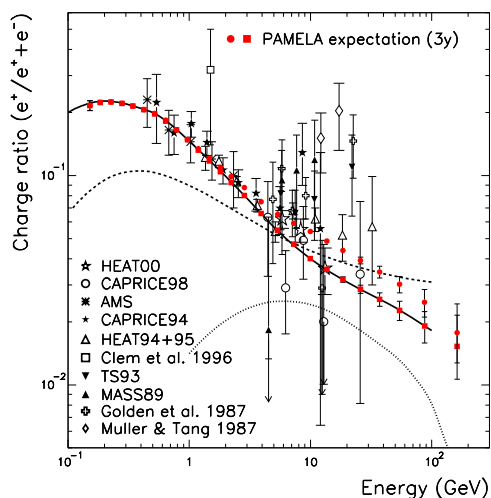


Figure 2: Positron fraction as a function of energy measured by several experiments. The dashed [7] and solid [8] lines indicate expectations from purely secondary production models, while the dotted line represents the contribution of the annihilation of a $336 \text{ GeV}/c^2$ neutralino [9]. The PAMELA expectations after three years of data taking are shown as in figure 1.

Galactic Cosmic Rays

The Pamela instrument is performing accurate measurements of the electron, proton and light nuclei energy spectra over wide dynamic ranges.

Since electrons with energy above 100 MeV rapidly lose their energy due to synchrotron radiation and inverse Compton processes, the discovery of primary electrons with energy of the order of TeV would evidence the existence of cosmic ray sources in the nearby interstellar space. On the other side, the determination of the proton and helium absolute fluxes will give information about the early Universe, whereas the nuclei composition and energy spectra measurements will allow us to learn about the origin and evolution of the matter content of our galaxy; both spectra are related to fundamental physical processes that govern the dynamics of the Universe. The secondary/primary ratios of cosmic ray nuclear and isotopic abundances such as B/C, Be/C, Li/C and $^3\text{He}/^4\text{He}$ are studied with high statistics. The ratios between “secondary” and “primary” nuclei, where the “primary” is directly produced by stellar nucleosynthesis, while the “secondary” is produced by fragmentation of primaries that interact with the matter of the interstellar medium, are directly related to the encountered amount of matter and to the nuclei lifetime before escaping from the galaxy. Then, the measurements Pamela is performing will constrain existing production and propagation models in the galaxy, providing detailed information on the galactic structure and the various mechanisms involved.

Another key question is whether the cosmic rays are continuously accelerated over their entire lifetime, or whether the acceleration occurs just once. The antiproton spectrum is of particular interest because of the “kinematic threshold” of antiproton production. Pamela is measuring accurately the sharp cutoff of the antiproton spectrum below 1 GV/c, in order to determinate whether there is any continuous acceleration, or deceleration, in the Galaxy.

Solar Physics and Trapped Particles

Beyond the primary objectives listed above, PAMELA is addressing issues related to the solar and the terrestrial environments (above 50 MeV) such as solar modulation, solar energetic particle (SEP) events (isotopic composition of H and He, e^- and, for the first time, e^+ spectrum) and composition and temporal dependence of the trapped and

albedo particle component. The PAMELA mission takes place in the recovery phase of solar minimum toward the maximum of the 24th solar cycle. In this period it will be possible to observe solar modulation of galactic cosmic rays due to increasing solar activity. Concerning the solar activity, about 10 significant solar events with energy high enough to be detectable are expected to occur during the lifetime of the experiment. The observation of SEP events with a magnetic spectrometer over an unprecedented energy range makes possible several aspects of solar and heliospheric cosmic ray physics to be addressed for the first time. Finally, the semipolar orbit of the Resurs-DK1 satellite allows for continuous monitoring of the electron and proton belts. The high energy component of the inner (proton) Van Allen belt, crossed by the Pamela instrument in the South Atlantic region, is monitored in detail with the magnetic spectrometer. The counting rates measured by the ToF and anticoincidence scintillators permit to extend measurements of the particle spectra to lower energies (3.5 MeV for e^- and 36 MeV for p). Due to the precession of the satellite orbit and its ellipticity, it is possible to perform a detailed 3-dimensional (latitude, longitude, altitude) mapping of the Van Allen Belts showing spectral and geometrical features.

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