Detection of Antimatter in our Galaxy

Piergiorgio Picozza and Roberta Sparvoli
University of Rome Tor Vergata and INFN Roma Tor Vergata, Rome, Italy
E-mail: piergiorgio.picozza@roma2.infn.it, roberta.sparvoli@roma2.infn.it

Abstract. Searching heavy antimatter and dark matter signals has considerably progressed in the recent years with the PAMELA space mission and the long duration balloon-borne BESS Polar experiments. The AMS-02 instrument is almost ready to be installed on board of the ISS at the end of July 2009. Interesting results have been obtained from PAMELA experiment on the antiproton to proton and positron to all electron ratios. The positron fraction shows an increasing at energies above 10 GeV, mostly interpreted as due to contributions from exotic sources, as dark matter or pulsars.

1. Introduction
Secondary Cosmic Rays in the terrestrial atmosphere have been for forty years the only tool to study physical processes at energies exceeding several orders of magnitude those available from natural radioactivity. Particle Physics born and developed studying cosmic rays, and positrons, muons, pions and strange particles were discovered detecting directly cosmic radiations or products of their interaction with matter targets. It took four decades of technological efforts to reproduce cosmic rays energies with accelerators and to compete in intensity. Three decades later technical developments of space particle detectors allowed the study of cosmic rays with energies largely exceeding those supplied by accelerators, opening new possibilities for the study of one of the most important issue facing astrophysics and cosmology today: what was the role of matter and antimatter in the early Universe? Is there antimatter on a cosmological scale? Is the present Universe baryon-symmetric? Although theoretical arguments based on the cosmic diffuse gamma-ray spectrum constrain the distance to any hypothetical domains of antimatter to be comparable to the horizon scale, the apparent baryon asymmetry in the Universe can be probed by searching for antinuclei in the cosmic radiation.

A wide program of direct antimatter search was triggered from the results obtained in 1979 by the balloon borne experiments of R. Golden [1] and E. Bogomolov [2] that identified the first antiprotons in cosmic rays. The detected antiproton spectrum largely exceeded the expected antiproton flux produced in interaction of cosmic rays with the interstellar matter. These data were interpreted in terms of primordial antimatter coming from antimatter domains in a baryonic symmetric Universe, of evaporation by Hawking effect of primordial mini black holes, or of exotic particles annihilation. Several experiments, focused on antimatter detection, followed the first ones, mainly performed by the WiZard, BESS and HEAT collaborations on board stratospheric balloons, and by AMS-01 on board the Space Shuttle. The core of these instruments was a magnetic spectrometer associated with some detectors for the hadronic and electromagnetic component identification. The experimental limits obtained by these missions for the $\overline{He}/He$ ratio are presented in fig. 1: the current lowest limit is obtained combining all BESS flights.
reaching a value of the order of $3 \times 10^{-7}$. As for the antiproton/proton ratio, the first pioneer results were not confirmed later.

At the same time experimental cosmology was progressing and another issue became very intriguing and fascinating: what kind of matter the Universe is made of? Actually, the WMAP data strongly suggest that the energy budget of the Universe is shared among baryonic matter (4%), dark (unknown) matter (23%) and dark energy (73%). The favourite candidates for the non-baryonic matter component are electrically-neutral weakly interacting massive particles (WIMP’s) with a mass in the range between 10’s of GeV to TeV. The most studied is the lightest neutralino $\chi$, in R-parity conserving supersymmetric models. Another interesting WIMP candidate is the lightest Kaluza-Klein particle in the Universal Extra Dimension framework. WIMPS should pervade the Milky Way halo and be concentrated at the galactic centre. As they mutually annihilate, they should produce high energy photons and matter and antimatter particles, mixed with a huge background produced by interaction of cosmic rays with the ISM. In figs. 2 and 3 the experimental available results for the antiproton to proton and positron to electron ratios, obtained by the balloon borne and AMS-01 experiments, are reported together with different calculations accounting for a pure secondary component [3, 4, 5, 6]. No clear conclusion can be obtained, showing that experiments at higher energies, better knowledge of the background, higher statistics and continuous monitoring of solar modulation are mandatory to disentangle possible exotic components from the standard production. The space missions PAMELA and AMS-02 and the long duration flights of the balloon borne BESS experiments were conceived to realize this venture.

2. The PAMELA and AMS-02 Space Missions
The primary scientific objectives of PAMELA (fig. 4) and AMS-02 (fig. 5) are the search for heavy antimatter and nonbaryonic particles outside the Standard Model. In particular they can search for anti-helium (primordial antimatter), heavy anti-nuclei (anti-stars), new matter in the

Figure 1. The ratio of anti-helium to helium in the cosmic radiation shown as a function of rigidity. No observation of anti-helium has been made to date and so upper limits are shown.
Figure 2. Recent experimental results for the antiproton to proton ratio along with theoretical calculations for pure $\bar{\pi}$ secondary production [3, 4, 5, 8].

Figure 3. The positron fraction as a function of energy measured by several experiments. The solid line is a calculation of the secondary positron fraction [6, 9].

Universe (strangelets?). They can perform also precise measurements of the antiparticle energy spectrum to unravel possible contributions from exotic sources and do accurate studies of nuclei and their isotopes to test cosmic-ray propagation models. Concomitant goals include the study of solar physics and solar modulation, the investigation of the interaction of cosmic-rays with the Earth’s magnetosphere and the search for high energy electrons to discover local sources.

2.1. The PAMELA mission

PAMELA - a Payload for Matter-Antimatter Exploration and Light Nuclei Astrophysics [7] - is an instrument realized by an Italian, Russian, German and Sweden collaboration and launched into space on board of the Russian satellite DK1 by a Soyuz-U rocket from the Baikonur cosmodrome in Kazakhstan on June 15th 2006. The satellite orbit is elliptical and semi-polar, with an altitude varying between 350 km and 610 km, at an inclination of 70°. Since July 2006 PAMELA is daily transmitting 16 Gigabytes of data to the Moscow ground segment. The instrument, shown in fig. 4, is constituted by a permanent magnet with a microstrip silicon tracker, a plastic scintillator time-of-flight system, a silicon-tungsten electromagnetic imaging calorimeter, a neutron detector, an anticoincidence system, a shower tail catcher scintillator. The combination of these devices allows antiparticles to be reliably identified from a large background of other charged and their fluxes to be measured in a wide range of energy.

PAMELA has recently published results concerning the antiproton to proton flux ratio [8] and the positron to all electrons fraction [9]. The $\bar{\pi}/p$ ratio, measured in the energy interval between 1 GeV and 100 GeV, is shown in fig. 6 and compared with recent results from other experiments and with theoretical calculations assuming pure secondary production of antiprotons during the propagation of cosmic rays in the galaxy [8]. The ratio increases smoothly from about $4 \times 10^{-5}$ at a kinetic energy of 1 GeV and levels off at about $1 \times 10^{-4}$ for energies above 10 GeV. The results on the $\bar{\pi}/p$ ratio do not show any particular feature to be referred to some relevant exotic source contribution. However, they allow tight constraints to be placed on many dark matter models, on parameters relevant for secondary production calculations and on contribution of hypothetical local cosmic-ray components.

The measured positron to all electron fraction in the range 1-100 GeV is shown in fig. 7,
compared with other recent measurements and a calculation for pure secondary production of positrons [9]. Below 5 GeV PAMELA data are lower than most of the other data and are in agreement with the results from the AESOP balloon-borne experiment, which flew in June 2006. At higher energies the PAMELA positron fraction is compatible with other measurements, but the significantly higher statistics clearly shows that the positron fraction increases with energy, in contrast with the theoretical decrease expectation. This excess of positrons has led to many speculations about its origin, as annihilation or decaying of dark matter, cosmic strings, young pulsar positron contribution, some inhomogeneity in SNR distribution in the Galaxy, standard astrophysics background.

A rise in the positron fraction at high energy has been postulated for the annihilation of dark matter particles in the galactic halo. The most problematic theoretical challenge posed by the PAMELA results is the asymmetry between leptonic (positron fraction) and hadronic (antiproton-proton ratio), difficult to explain in the framework where the neutralino is the dominant dark matter component [10]. In this case suitable explanation requires a very high mass (M=10 TeV) neutralino which, however, is not in a favoured part of the supersymmetric phase space. Better explanations are obtained in terms of leptonic annihilation channel for a wide range of the WIMP mass [10]. This, however, would disfavour the neutralino, since, as a Majorana particle, it cannot annihilate directly into light fermions with large rates, due to helicity suppression. More preferred would be the Kaluza-Klein lightest stable particle that, as a boson, can directly annihilate into $e^+e^-$ pairs with no helicity suppression factor. It is worth noting, however, that all explanations in terms of dark matter annihilation request a boost factor for the annihilation standard rate ranging between $10^2$ to $10^4$. Calculations [11, 12] for both hypotheses are shown in figs. 8 and 9.

Another explanation asks for a contribution from nearby and young pulsars. Primary
electrons are accelerated in the magnetosphere of pulsars in the polar cup and in the outer gap along the magnetic field lines, emitting gamma rays by synchrotron radiation, gammas that in presence of the pulsar’s gigantic magnetic field can evolve in positron and electron pairs. These, after an additional acceleration, are trapped in the cloud surrounding the pulsar, and about 10000 years later escape into the interstellar medium, giving a further contribution to the electron and positron components [13, 14].

On the other hand, standard secondary production to explain this anomalous increasing of the ratio would demand high modifications in the current knowledge of the electrons, protons and helium spectra, although some papers report an explanation of this increasing in terms of few nearby SNR or of secondary production taking place in the same region where cosmic rays are being accelerated [15, 16]. PAMELA is performing accurate measurements of the absolute fluxes of electrons, positrons, protons and light nuclei, that will tightly constrain the secondary production models. The difference in the lower energy part of the spectrum between PAMELA data and almost all previous measurements is interpreted as a consequence of time and charge dependent solar modulation effects. PAMELA data have been collected in solar phase $A^-$, where the magnetic dipole projection on the solar rotational axis and the rotational axis itself are anti-parallel. In the $A^+$ phase, the situation is inverted. The charge sign-dependent effect of the solar modulation is different between the two phases, due to a systematic deviation from reflection symmetry of the interplanetary magnetic field [17].

We remind that also Fermi satellite [18] and ATIC balloon borne [19] experiments reported very interesting results on the total electron flux, that have been interpreted in terms of dark matter or pulsar contributions, but their instruments do not allow to distinguish between matter and antimatter components.

2.2. AMS-02 on the ISS

The AMS-02 instrument [20] has been realized by a worldwide collaboration and will be installed outside the International Space Station at the end of July 2010. The detector (fig. 5) has a size of $\sim 3$ m$^3$ and the weight of 7 tons. At present, it is in final assembling and testing phase at CERN.

The main detector of AMS-02 is a magnetic spectrometer composed of a magnet constituted...
of 12 superconducting coils with a magnetic field of $\sim 0.9$ T and a bending power of $\sim 0.8$ T$\times$m$^2$, and of a tracking system made of 8 layers, each of 0.8 m$^2$, for a particle rigidity measurement up to few TeV. Complementary detectors are a Transition Radiation Detector, composed of 328 modules made of fleece radiators and straw tube arranged in 20 layers assembled in an octagonal shape structure, a trigger and Time- of-Flight system, consisting of 4 scintillator planes for a total of 34 crossed scintillator paddles, a Ring Imaging Detector, constituted by 2 different radiators - respectively an Aerogel and a Sodium fluoride - a conical reflector and a matrix of 680 photomultipliers. To improve the discrimination between the hadronic and the leptonic components, an electromagnetic calorimeter of 17 radiation lengths is added at the bottom of the apparatus; it is made of 9 superlayers of lead scintillating fiber sandwiches disposed, alternatively, along the X and Y directions. The calorimeter measures gamma-rays, electrons and positrons and separate leptons from hadrons with a rejection power of $10^3 - 10^4$ in the energy range from 1 GeV up to 1 TeV.

The combination of all these detectors allows high precision and high statistics in the search for light and heavy antimatter in space, and in the measurement of cosmic rays spectra and chemical composition up to 1 TeV . In particular AMS-02 will improve the PAMELA positron and electron data, extending the measurements up to 800 GeV with high statistics. The detector is also a powerful gamma detector. A unique feature of AMS-02 is the combined searches in different channels - antiprotons, positrons, antideuterons, gammas - that will considerably increase sensitivity to SUSY DM signals detection.

3. Polar Ballon Flights

Long duration polar flights represent a new interesting opportunity for cosmic rays research, at a low cost with respect to space missions.
On December 2004 the BESS (Ballon Borne Experiment with a Superconducting Spectrometer) Polar I experiment, an American-Japanese collaboration, made its first successful polar flight in Antarctica, 8.5 days long, detecting 1520 antiprotons in the energy range 0.1-4.2 GeV. The instrument was composed by a superconducting solenoid magnet, with 1 T magnetic field, combined with internal JET and drift chambers giving an MDR of \( \sim 200 \text{ GeV} \), a Time-Of-Flight hodoscope with 3 sets of scintillators placed, respectively, one on the top and two on the bottom of the solenoid vessel, and an aerogel Cherenkov counter for \( e/\mu \) rejection. The scientific objectives were the search for antiparticle and antimatter in the low energy region and the precise measurements of various primaries cosmic rays. The main results in the \( \text{He}/\text{He} \) and \( \overline{p}/p \) ratios are shown in fig. 1 and 2, respectively.

A real quality improvement on long duration flights has been done on 23rd of December 2008, when the BESS Polar II experiment was launched from William Field, McMurdo, in Antarctica. The floating time was of 29.5 days with 24.5 days of data taking. Promising results on \( \overline{p}/p \) ratio and on the \( D \) and \( \text{He} \) search are expected from the analysis of the collected data.

Other long duration flights are planned for the next years. PEBS (Positron Electron Balloon Experiment) has been designed to measure positrons and electrons in the energy range from 0.5 GeV to 200 GeV and will be launched from Arctica Swallbard base. GASP from Antarctica and DbarSUSY from Arctica experiments will be dedicated to anti-deuteron search at very low energy.

4. Summary
The search of antimatter and dark matter signals in space has largely developed in the last years by the ATIC and BESS balloon-borne and PAMELA and Fermi satellite experiments. Results from the PAMELA instrument show very interesting features in the positron to all electron fraction, compared to expectation from the standard secondary production. Such features are mainly interpreted in terms of positron primary sources, as dark matter annihilation or nearby pulsars contributions. Explanations in terms of nearby SNR’s or non standard processes in the secondary positrons production are also reported. The antiproton to proton spectrum appears in agreement with the standard secondary production. AMS-02 is now ready to start, and will complete - through different observation channels - the exploration at higher energy and with better statistics.

5. References
[1] R. L. Golden et al., Phys. Rev. Lett., 43 (1979), 1196.
[2] E. Bogomolov et al., XX Int. Cosmic Ray Conf., 2 (1987), 72.
[3] A. Molnar and M. Simon, XXVII Int. Cosmic Ray Conf., (2001), 1877.
[4] L. Bergstrom, J. Edsjo and P. Ullio, ApJ, 526 (1999), 215.
[5] I. V. Moskalenko et al., ApJ, 565 (2002), 280.
[6] I. V. Moskalenko and A. W. Strong, ApJ, 493 (1998) 694.
[7] P. Picozza et al., Astrop. Phys., 27 (2007), 296.
[8] O. Adriani et. al., PRL, 102 (2009), 051101.
[9] O. Adriani et. al., Nature, 458 (2009), 697.
[10] M. Cirelli et al., Nucl. Phys. B, 813 (2009), 1.
[11] L. Bergstrom, T. Bringmann and J. Edsjo, Phys. Rev. D, 78 (2008), 103520.
[12] D. Hooper and K. M. Zurek, arXiv:0902.0593 (2009).
[13] H. Yuksel, M. D. Kistler and T. Stanev, arXiv:0810.2784 (2008).
[14] D. Hooper, P. Blasi and P. D. Serpico, JCAP, 0901 (2009), 025.
[15] N. J. Shaviv, E. Nakar and T. Piran, arXiv:0902.0376 (2009).
[16] P. Blasi, arXiv:0903.2794 (2009).
[17] J. Clem et al., ApJ, 464 (1996), 507.
[18] A. A. Abdo et al., PRL, 102 (2009), 181101.
[19] J. Chang et al., Nature, 456 (2008), 362.
[20] B. Beischer et al., New Journal of Physics, 11 (2009), 105021.